Magnetic Diffusion and Its Applications in Bulk High-T_c Superconductors

Y. S. Cha

Energy Technology Division, Argonne National Laboratory, Argonne, Illinois 60439, USA

Magnetic diffusion in bulk high-T_c superconductors is important in electric power applications because the time scale associated with it is the same order of magnitude as the period of an AC system with frequency in the range of 50–60 Hz. It is shown that Bean's critical-state model is applicable for equilibrium conditions but not for AC steady-state conditions. Furthermore, to accurately predict the time evolution of the magnetic field distribution in bulk high-T_c superconductors, one must simultaneously solve magnetic- and thermal-diffusion equations. Magnetic-diffusion equations can be applied to AC losses and other phenomena observed in many applications for bulk high-T_c superconductors, including inductively coupled fault current limiters and trapped-field magnets using a pulsed current supply.

PACS numbers: 74.25.Ha

I. INTRODUCTION

In the study of superconductors, the most powerful tool is Bean's critical-state model [1]. Bean's model works well for low-T_c superconductors because the critical current density is high as a result of strong flux pinning. It is used to determine the critical current density (from magnetization measurement), the AC hysteresis loss, levitation forces, etc. For high-T_c superconductors, however, the pinning is not as strong as for the low-T_c superconductors. Furthermore, high-T_c superconductors usually operate at much higher temperatures; consequently, magnetic relaxation (thermally activated flux creep) becomes important [2]. These factors make Beans critical state model less useful for high-T_c superconductors, particularly under AC steady-state conditions, where a majority of the applications of bulk high-T_c superconductors are expected to be.

In this paper, we describe experimental and analytical results recently published on magnetic diffusion. A general equation for magnetic diffusion is derived from Maxwell's equations under the magnetoquasistatic condition. We show that Bean's critical-state model is valid only for the equilibrium condition, and it satisfies the magnetic diffusion equation under the steady-state condition. We demonstrate that Bean's profile is not approached under AC steady-state conditions for bulk high-T_c superconductors. Depending on the operating conditions, magnetic diffusion may play a dominant role in determining the transient response of high-T_c superconductors for various applications, including inductive fault current limiters [3–7] and trapped-field magnets [9–11], and in evaluating AC losses [8].

II. MAGNETIC DIFFUSION

Even though Maxwell's equations are linear, the constitutive relations are nonlinear for high-T_c superconductors. The resistivity is a function of current density, magnetic field, and temperature. High-T_c superconductors usually follow the so-called power law (nonlinear E/J relationship) as a result of magnetic relaxation [2]. The magnetization process is also nonlinear (nonlinear B/H relation). The two nonlinear phenomenological relationships can be expressed as

$$\boldsymbol{B} = \boldsymbol{B}(\boldsymbol{H}) \tag{1}$$

and

$$\boldsymbol{E} = \rho(J, B, T)\boldsymbol{J}\,, \tag{2}$$

where $\boldsymbol{B}$ is magnetic flux density, $\boldsymbol{H}$ is magnetic field strength, $\boldsymbol{E}$ is electric field strength, $\boldsymbol{J}$ is current density, T is temperature, and ρ is resistivity. The magnetoquasistatic forms of the Maxwell equations [1] are

$$\nabla \times \boldsymbol{H} = \boldsymbol{J} \tag{3}$$

and

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}\,. \tag{4}$$

In this paper, the bold letters indicate vectors.

Substituting Eqs. (2) and (3) into Eq. (4), we obtain

$$\nabla \times [\rho(J, B, T)\nabla \times \boldsymbol{H}] = -\frac{\partial \boldsymbol{B}(\boldsymbol{H})}{\partial t}\,, \tag{5}$$

where $\boldsymbol{B}$ is explicitly expressed as a function of $\boldsymbol{H}$. Eq. (5) is nonlinear both electrically and magnetically; it is electrically nonlinear because the resistivity is a function of current density J, and it is magnetically nonlinear because the magnetic flux density $\boldsymbol{B}$ is, in general, a nonlinear function of $\boldsymbol{H}$. Eq. (5) can be used to calculate both the ρJ^2 loss and the hysteresis loss under AC steady-state conditions. Both losses are important when the applied field is relatively low, and the magnetization M in the superconductor is not negligible. When the applied field $\boldsymbol{H}$ is large when compared with $\boldsymbol{M}$, ρJ^2 loss becomes dominant, and hysteresis loss can be neglected. Magnetic hysteresis arises because of the nonlinear B/H curve. $\boldsymbol{B}$ and $\boldsymbol{H}$ are related through the average magnetic moment per unit volume $\boldsymbol{M}$ by the following equation:

$$\boldsymbol{B} = \mu_0(\boldsymbol{H} + \boldsymbol{M})\,. \tag{6}$$

When the applied field is large when compared with the magnetization in the superconductor ($\boldsymbol{H} \gg \boldsymbol{M}$), $\boldsymbol{B}$ becomes linearly proportional to $\boldsymbol{H}$, i.e.,

$$\boldsymbol{B} = \mu_0 \boldsymbol{H}\,. \tag{7}$$

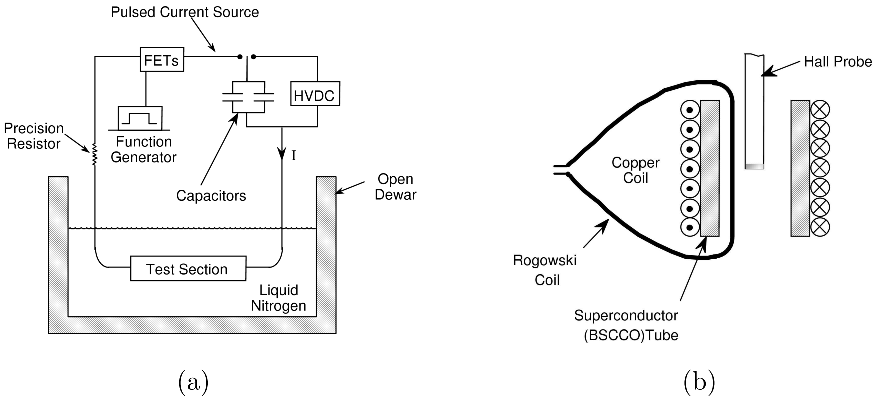

FIG. 1: Schematic diagram of the experimental apparatus for magnetic diffusion: (a) current supply and (b) test section.

Substituting Eq. (7) into Eq. (5) led to the following nonlinear magnetic diffusion equation:

$$\nabla \times [D_m(J,B,T)\nabla \times \boldsymbol{B}] = -\frac{\partial \boldsymbol{B}}{\partial t}\,, \tag{8}$$

where the magnetic diffusion coefficient $D_m(J,B,T) = \rho(J,B,T)/\mu_0$. Eq. (8) is still nonlinear, but it is simpler than Eq. (5). However, by ignoring the nonlinear relationship between $\boldsymbol{B}$ and $\boldsymbol{H}$, the ability to predict hysteresis loss under AC steady-state conditions no longer exists. Nevertheless, Eq. (8) is still a useful approximation under certain conditions. For one-dimensional slab geometry, Eq. (8) is reduced to

$$[\partial\left(D_m \partial B_z/\partial x\right)/\partial x] = \partial B_z/\partial t\,. \tag{9a}$$

For one-dimensional cylindrical geometry, the magnetic diffusion equation is

$$[\partial\left(D_m r \partial B_z/\partial r\right)/\partial r]/r = \partial B_z/\partial t\,. \tag{9b}$$

Eq. (9a) or (9b) is a scalar equation and is similar to the heat conduction equation. It describes how the magnetic flux density propagates through the superconductor with a magnetic diffusivity D_m.

Magnetic diffusion is clearly demonstrated by the simple experiment [12] shown in Fig. 1. The test section, which consists of a copper coil and a cylindrical superconductor tube, is submerged in a pool of liquid nitrogen. The superconductor tube of bulk $Bi_2Sr_2CaCu_2O_x$ (BSCCO-2212) was made by melt-casting. A Hall probe near the center of the tube is used to measure the magnetic field in the cavity of the tube. A Rogowski coil measures the induced current in the superconductor tube. The copper coil is connected to a pulsed-current source, which consists of several capacitors in parallel and an array of field-effect transistors (FETs), as shown schematically in Fig. 1a.

Typical experimental results are shown in Fig. 2, where N is the number of turns of the copper coil, I is the current in the coil, and H is the magnetic field strength measured

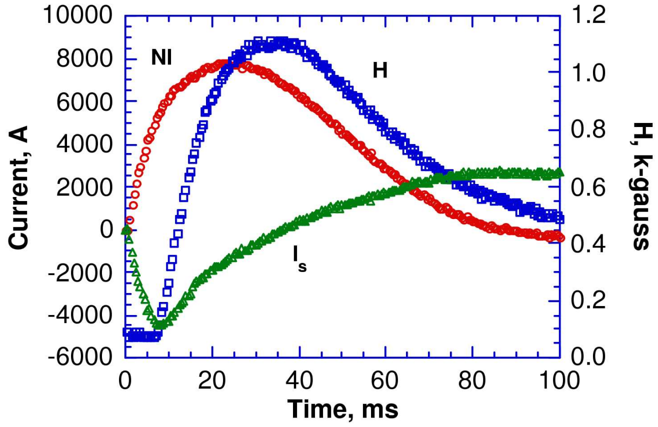

FIG. 2: Experimental results showing the time delay between the peak NI and the peak H.

by the Hall probe. One notable observation is that there is a time delay between the peak in NI and the peak in H. This delay is due to the presence of the superconductor tube between the copper coil and the Hall probe. If the superconductor tube is removed from the experiment, there is practically no time delay between the NI and the H peaks. This shift occurs because the magnetic field propagates very fast in a nonconducting (the resistivity is very high) medium such as air or liquid nitrogen. When the superconductor tube is placed between the copper coil and the Hall probe, it slows down the speed of propagation considerably because the superconductor has a resistivity much lower than that of either air or liquid nitrogen. Lower resistivity resulted in lower magnetic diffusivity, which resulted in slower propagation of the magnetic field through the superconductor. As a matter of fact, the time delay between the NI and the H peaks can be used as an indication of the quality of the superconductor. The longer the time delay, the better (higher critical current density) the superconductor. Smaller time delay indicates a poor superconductor with relatively low critical current density.

The reason that magnetic diffusion in the high-T$_c$ superconductor is important for transient experiments is that the magnetic-diffusion coefficient D_m is relatively low because the resistivity ρ is very low in the vicinity of $J = J_c$. The characteristic time for magnetic diffusion is approximately

$$\tau = a^2/D_m = \mu_0 a^2/\rho \,, \qquad (10)$$

where a is the characteristic dimension (thickness) of the superconductor. The wall thickness of the BSCCO-2212 tube used in the experiments was 5.5 mm. At $E = 1\ \mu\text{V/cm}$, $\rho = 10^{-2}\ \mu\Omega$–cm. Substituting these values in Eq. (10), we found that $\tau = 380$ ms. The typical rise time of the applied field is ≈ 20 ms for the experiments reported in Ref. [12]. The characteristic time of an AC system with a frequency of 60 Hz is 16.7 ms. These characteristic times are shorter than that of magnetic diffusion in the superconductor with a thickness of 5.5 mm. Thus, there is not enough time for the applied field to reach steady state or to penetrate the superconductor tube. However, other factors such as heating and dissipation, to be discussed in Section IV, will increase the propagation speed of the magnetic field in the superconductor and significantly reduce the time for magnetic diffusion estimated by Eq. (10). The important point is that the characteristic time for magnetic diffusion of a bulk superconductor with a characteristic dimension of, say 1 to 10 mm, can be in the same order of magnitude as that of an AC system. Therefore, magnetic diffusion may be the dominant factor in bulk applications of high-T_c superconductors.

III. LIMITATION OF BEAN'S CRITICAL-STATE MODEL

It is worthwhile to comment on the applicability/validity of Bean's critical-state model because it is such a useful and powerful tool in analyzing various engineering/physical systems. The power law states that

$$E/E_c = (J/J_c)^n \,, \tag{11}$$

where the subscript c indicates the critical state. Bean's critical-state model is valid only if the superconductor exhibits very strong pinning (i.e., the exponent n is very large when compared with 1). The pinning of several high-T_c superconductors, particularly those for large-scale applications, may not be strong enough to satisfy Bean's model. Second, as pointed by Cha and Askew [12], Bean's critical-state model is valid only if the characteristic time for magnetic diffusion is much shorter than the characteristic time of the system. How fast the magnetic flux profile will approach Bean's limit depends on exponent n and the rate of change of the applied field. Eq. (11) shows that the resistivity increases with the exponent n, which means that the magnetic diffusion coefficient increases with n. The higher the n, the higher the rate of magnetic diffusion. If the rate of magnetic diffusion is large when compared with the rate of change of the applied field, Bean,s model should provide a fairly accurate description of the current and the magnetic flux profiles.

Bean's critical-state model states that the current density in the superconductor is either zero or equal to the critical current density J_c (the gradient of magnetic flux density is always constant and equal to the critical current density of the superconductor). For slab geometry, Eq. (9a) becomes

$$\partial\left(\rho J_c\right)/\partial x = \partial B_z/\partial t \,. \tag{12}$$

Inasmuch as $\rho J_c = E_c =$ a constant, we have $\partial B_z/\partial t = 0$. Therefore, Bean's critical-state model satisfies the steady-state solution of the magnetic-diffusion equation for slab geometry. If ample time is allowed for the magnetic flux density to reach its steady-state distribution (linear), Bean's critical-state model is applicable. Otherwise, one must solve the magnetic diffusion equation to calculate the time evolution of the magnetic field inside the superconductor.

For cylindrical geometry, substituting Bean's profile into Eq. (9b) led to

$$[\partial\left(D_m r \mu_0 J_c\right)/\partial r]/r = \partial B_z/\partial t\,. \tag{13}$$

Eq. (13) can be shown to be equivalent to

$$J_c\left(\rho/r + \partial\rho/\partial r\right) = \partial B_z/\partial t\,. \tag{14}$$

Because $J = J_c$ everywhere, ρ is constant, and $\partial\rho/\partial r = 0$. Furthermore, $E_c = \rho J_c$, Eq. (14) becomes

$$E_c/r = \partial B_z/\partial t \tag{15}$$

or

$$r\left(\partial B_z/\partial t\right)/E_c = 1\,. \tag{16}$$

Eq. (15) or (16) provides the criterion to determine whether Bean's model is applicable to cylindrical geometry. For example, if $E_c = 1$ μV/cm and $r = 1$ cm, $\partial B_z/\partial t = 10^{-2}$ T/s. If the external magnetic field changes at a rate $< 10^{-2}$ T/s, Bean's model is applicable because there is ample time to allow the magnetic flux density to reach Bean's profile, and one does not need to solve the magnetic-diffusion equation. However, if the rate of change of the external magnetic field is not small when compared with the rate given by Eq. (15), Bean's model will become less useful, and one must solve the magnetic-diffusion equation to determine the time evolution and space distribution of the magnetic flux density and current density in the superconductor.

IV. EFFECT OF DISSIPATION AND HEATING ON MAGNETIC DIFFUSION

The foregoing discussions are limited to an isothermal system, where the rate of heat generation is small, and the rate of heat transfer is adequate to keep the temperature of the superconductor constant. This situation can occur only if both the frequency and the amplitude of the applied field are small. In general, the resistivity of a superconductor is a function of the current density, applied field, and the temperature, $\rho = \rho(J, B, T)$. If the applied field is changing rapidly (faster than can be described by Bean's critical-state model), then a relatively large current density appears near the outer radius of the superconductor. The local current density can be significantly greater than the critical current density. There are two consequences when the local current density exceeds J_c. First, local resistivity increases. This relatively large increase in ρ will increase the rate of magnetic diffusion because the magnetic-diffusion coefficient D_m is linearly proportional to ρ. Second, when local ρ increases, so does dissipation (ρJ^2). If heat is not removed quickly enough from the superconductor, the local temperature will rise. When temperature rises, the resistivity increases, further increasing the magnetic-diffusion coefficient and speeding up the magnetic-diffusion process. Dissipation and heating will lead to a nonuniform temperature distribution in the superconductor, with relatively high temperature near the surface and relatively low temperature near the center. Both the higher current density and temperature near the surface tend to increase the speed of magnetic diffusion by increasing the local resistivity (and D_m). If heat is removed quickly enough from the superconductor, the heating effect is less important. But, if the rate of heat generation is larger than the rate of heat removal, then the superconductor tube will continue to heat up. When the temperature of the outside layers is heated above the critical temperature, those layers become transparent to the magnetic field. This phenomenon is similar to ablation, but it is magnetic rather than thermal.

The time evolution of the temperature distribution in the superconductor is governed by the heat conduction (diffusion) equation

$$[\partial\left(k\partial T/\partial x\right)/\partial x] + \rho J^2 = \gamma c\left(\partial T/\partial t\right) \ , \tag{17}$$

where k is thermal conductivity, T is temperature, γ is density, c is the specific heat of the superconductor, and t is time. During the transient, not only is there a boundary layer for magnetic flux density (and a corresponding one for current density), there is also a thermal boundary layer. Therefore, the magnetic- and thermal-diffusion equations must be solved simultaneously. Because Eqs. (9) and (17) are nonlinear, iterations are required. Once the magnetic flux density is determined from Eq. (9) at a particular instant, the current distribution is obtained from the Faraday equation. Then, Eq. (17) can be used to calculate the temperature distribution. From the calculated B, J, and T distributions, we can update the resistivity ρ. This process continues until the solution converges. This numerical calculation requires knowledge of the variation of ρ with current density, magnetic field, and temperature. The information on $\rho(J, B, T)$ can only be obtained from experimental data [13].

If the rate of heat transfer is negligible compared to the rate of heat generation, Eq. (17) reduces to the adiabatic equation

$$\rho J^2 = \gamma c \partial T/\partial t \tag{18}$$

and the temperature at any location can be obtained by integrating Eq. (18) with respect to time.

V. APPLICATIONS IN BULK HIGH-T$_c$ SUPERCONDUCTORS

Bulk high-T$_c$ superconductors have many potential applications in the electric power industry. One of the most likely early applications in electric transmission and distribution systems is a superconducting fault current limiter. Magnetic diffusion becomes important because the characteristic time of a 60 Hz power system is on the order of several milliseconds, which is comparable to the characteristic time of magnetic diffusion in a superconductor with a characteristic dimension of a few millimeters to one centimeter. Depending on the operating conditions, magnetic diffusion may also become important in evaluating

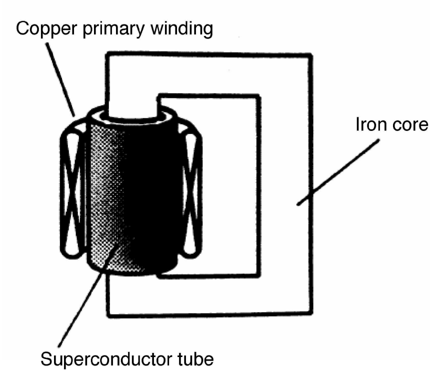

FIG. 3: Schematic diagram of an inductive fault current limiter, also known as a superconductor shielded core reactor (SSCR).

the AC losses of superconducting devices. Another potential application is the so-called trapped-field magnet. Because of its small volume (and weight), it may be advantageous to use the pulsed current to trap the magnetic field in a superconductor. Under such conditions, magnetic diffusion plays a dominant role during the process. We shall describe briefly each of these applications. Other potential applications, such as magnetic separation, magnetic shielding, and control and manipulation of magnetic particles in human tissues, will not be discussed here.

V-1. Inductive fault current limiter

One of the potential early applications of bulk high-T_c superconductors in the electric power industry is the inductive fault current limiter (FCL), also known as the superconductor shielded core reactor (SSCR). An SSCR, shown schematically in Fig. 3, is a passive device that consists mainly of a closed iron core inside a superconductor tube and a copper coil wound on the outside of the superconductor tube [3–7]. The SSCR uses the shielding capability of a superconductor tube to keep the impedance low under normal operating conditions. Under fault conditions, the high current in the copper coil exceeds the shielding capability of the superconductor tube, and the impedance jumps because the iron core is no longer shielded from the coil by the superconductor tube. The superconductor tube heats significantly during a fault. An equivalent circuit of an ideal transformer, based on the lumped parameter, can be used to explain the behavior of the SSCR quite well [7]. However, the transformer model has its limitations and can neither predict nor explain the important transient process during the early stage of the fault. For example, one of the most important parameters during an electric transient caused by a fault is the quench time (defined as the time when the SSCR begins to limit the fault current). Without understanding what is happening in the superconductor during the transient, the quench time can only be determined semi-empirically [14]. The field equations and the properties of the superconductor, such as the flux pinning strength, govern what happens in the su-

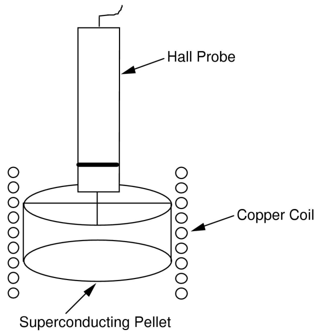

FIG. 4: Schematic diagram of the apparatus for trapped field experiments.

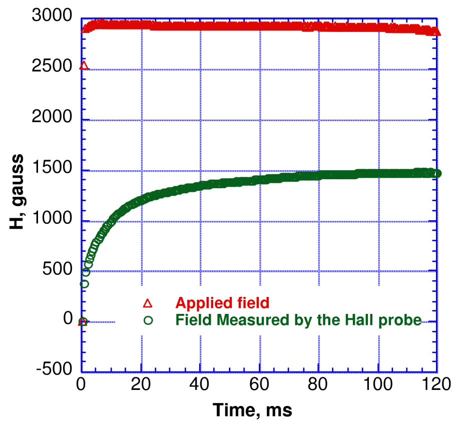

FIG. 5: Experimental results demonstrating the diffusion-dominated transient characteristics of an YBCO pellet subjected to a constant applied magnetic field.

perconductor. As shown in Ref. [8], based on the results of the linear magnetic-diffusion model, we can explain qualitatively what is happening in the superconductor tube during the transient, consistent with the lumped-parameter model of an ideal transformer. To predict quantitatively the transient behavior of the superconductor under the fault condition, one needs to solve simultaneously the coupled magnetic- and thermal-diffusion equations.

V-2. Trapped-field magnet

Magnetic diffusion can also be demonstrated by examining the transient response of a superconducting pellet subjected to a constant applied field [15]. The experimental apparatus is shown schematically in Fig. 4. An 80-turn copper coil is wound on a melt-textured YBCO pellet that is 27 mm in diameter and 10.5 mm thick. The axial length of the coil is approximately three times the thickness of the pellet, and the pellet is placed in the middle third of the coil. The coil and the pellet are submerged in liquid nitrogen. A Hall probe is placed 0.3 mm above the center of the pellet. The coil is excited by a pulsed-current supply like that shown in Fig. 1a. A typical result of the experiment is shown in Fig. 5. A step profile is deliberately maintained for the applied field, and the transient response of the pellet is measured by a Hall probe. Initially, the field rises sharply and, with time, the rate of increase decreases. At 100 ms, the field changes slowly, and steady state is approached. This behavior is typical of a diffusion-dominated process [15]. A group at Nagoya University [9–11] reported the results of flux trapping in YBCO pellets. They measured the radial magnetic flux density distribution in the superconductor pellet (see Fig. 4 of Terasaki *et al.* [9]). Their results clearly show that during the transient, Bean's profile of linear magnetic flux distribution was not reached. They also attributed some of the experimental observations to heat generation in the superconductor. To predict these experimental results, we must again simultaneously solve the magnetic and thermal diffusion equations described previously.

V-3. AC losses

If current in the superconductor can be divided into a transport (or conduction) current and a magnetization current, AC loss (-Q) derived from Maxwell's equations leads to [16–17] the equation

$$-Q = \oint dt \int_{\mathrm{HTS}} \boldsymbol{J} \cdot \boldsymbol{E} dV + \oint dt \int_{\mathrm{HTS}} \boldsymbol{H} \cdot \frac{\partial \boldsymbol{M}}{\partial t} dV \, , \tag{19}$$

where $\boldsymbol{E}$ is the electric field strength, $\boldsymbol{H}$ is the magnetic field strength, $\boldsymbol{M}$ is the average magnetic moment per unit volume, and V is the volume of the superconductor (the bold letters indicating vectors). The volume integral is over the superconductor (HTS), and the time integral is over one cycle. The only assumption is that energy stored in the electric field is small when compared with that stored in the magnetic field. The first term on the right-hand side (RHS) of Eq. (19) is due to transport (or conduction) current, while the second term is due to magnetization current.

If true steady state is reached in the superconductor, then Bean's critical-state model, which assumes that a superconductor can carry a constant lossless current density known as the critical current density, is expected to apply. Under these circumstances, the first term on the RHS of Eq. (19) vanishes because the transport current is lossless ($J = J_c$ and $E = 0$). The second term on the RHS of Eq. (19) is not zero because the superconductor contains a trapped field (the result of flux pinning) inside. After a cycle, the magnetic field inside the superconductor does not return to zero. A result of hysteresis will be loss, given by the second term on the RHS of Eq. (19). The volume integral of this second term is equal to the area enclosed by the magnetization loop in a typical plot of M vs. H. This area, times the volume of the superconductor, is equal to the power loss of the superconductor over one cycle. Thus, the second term is indeed the hysteresis loss as calculated by Bean and others.

Under dynamic (nonsteady-state) conditions, hysteresis loss still occurs because a trapped field is present inside the superconductor after a cycle. The important point is that, under dynamic conditions, the first term on the RHS of Eq. 19 can no longer be neglected, because true steady state is not reached, and Beans profile is not approached under AC steady-state operation. The dynamic loss is the result of magnetic diffusion in the superconductor. The first term on the RHS of Eq. (19) represents the Joule heating loss, whereas the second term represents the hysteresis loss. In general, both types of losses are present. For the FCL described previously, the AC losses depend on the operating conditions of the device. Under fault conditions, the dominating loss is from the Joule heating due to magnetic diffusion because the induced current is very large in the superconductor. Under continuous normal operation, with operating current well below the critical current of the superconductor, the dominating loss is from hysteresis because joule heating loss is negligible. If the device is operating very close to the critical current of the superconductor, then both losses are important.

VI. SUMMARY

Magnetic diffusion is important for applications of bulk high-T_c superconductors. This is because the characteristic time for magnetic diffusion in bulk high-T_c superconductors is in the same order of magnitude as that of an AC system with frequency in the 50–60 Hz range. The classical critical-state model is shown to be inadequate for bulk high-T_c superconductors in practical applications because Bean's profile is not approached in an AC steady-state system. Furthermore, we found that to predict accurately the time evolution of the magnetic flux density and current density distributions in the superconductor, one must solve simultaneously the coupled magnetic- and thermal-diffusion equations. The importance of magnetic and thermal diffusion in several applications, including inductive fault current limiter and trapped-field magnet, is discussed. We found that in evaluating AC losses in practical applications, losses due to both hysteresis and Joule heating should be included.

Acknowledgments

This work was supported by the U.S. Department of Energy, Office of Electric Transmission and Distribution, as part of a program to develop electric power technology, under Contract W-31-109-Eng-38.

References

[1] T. P. Orlando and K. A. Delin, *Foundations of Applied Superconductivity* (Addison-Wesley, Reading, Massachusetts, 1991), Chap. 7.
[2] Y. Yeshurun, A. P. Malozemoff, and A Shaulov, Rev. Mod. Phys. **68**, 911 (1996).
[3] W. Paul *et al.*, Supercond. Sci. Technol. **10**, 914 (1997).
[4] J. Cave *et al.*, IEEE Trans. Appl. Supercond. **9**, 1335 (1999).

[5] V. Meerovich *et al.*, IEEE Trans. Appl. Supercond. **9**, 4666 (1999).
[6] J. Nakatsugawa *et al.*, IEEE Trans. Appl. Supercond. **9**, 1373 (1999).
[7] M. G. Ennis, T. J. Tobin, Y. S. Cha, and J. R. Hull, IEEE Trans. Appl. Supercond. **11**, 2050 (2001).
[8] Y. S. Cha, Physica C **361**, 1 (2001).
[9] A. Terasaki, Y. Yanagi, Y. Itoh, M. Yoshikawa, T. Oka, H. Ikuta, and U. Mizutani, in Proc. 10th Int. Symp. on Superconductivity 2, Gifu, Japan, Oct. 27-30, 1997, pp. 945-948.
[10] Y. Itol, Y. Yanagi, and U. Mizutani, J. Appl. Phys. **82**, 5600 (1997).
[11] U. Mizutani, T. Oka, Y. Itol, Y. Yanagi, M. Yoshikawa, and H. Ikuta, Appl. Superconductivity **6**, 235 (1998).
[12] Y. S. Cha and T. R. Askew, Physica C **302**, 57 (1998).
[13] Y. S. Cha, IEEE Trans. Appl. Supercond. **13**, 2028 (2003).
[14] Y. S. Cha, A Semi-Empirical Correlation for the Quench Time of an Inductively Coupled Fault Current Limiter, paper to be presented at 2004 Applied Superconductivity Conference, Jacksonville, Florida, Oct. 3-8, 2004.
[15] Y. S. Cha, Physica C **330**, 1 (2000).
[16] W. J. Carr, Jr., Physica C **310**, 1 (1998).
[17] W. J Carr, Jr., in Advances in Cryogenic Engineering (Materials) (Plenum Press, New York, 1998), Vol. 44, pp. 585-592.