

## Direct current voltage increment due to ac coupling in a high $T_c$ superconducting coil

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The voltage–current characteristics of a superconducting coil, made of multifilamentary silver-sheathed  $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10+\delta}$  tape, are investigated. We find that a small ac current  $I_{ac}$  superimposed on a relatively large dc current  $I_{dc}$  causes a significant increase in the coil dc voltage, approximately proportional to  $I_{dc}$ ,  $I_{ac}^2$ , and the ac frequency. We attribute this effect to the nonlinear magnetoresistance of the coil, and discuss its significance in power applications of high  $T_c$  superconducting coils, such as fault current limiters and superconducting magnetic energy storage devices. © 1998 American Institute of Physics. [S0003-6951(98)02352-3]

The recent progress in manufacturing multifilamentary silver-sheathed  $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10+\delta}$  superconducting tapes has resulted in relatively long wires with improved electrical and mechanical characteristics.<sup>1,2</sup> This progress has enabled the fabrication of high-temperature superconducting (HTS) coils for the construction of power devices such as magnets, transformers, motors, generators, fault current limiters (FCLs), and superconducting magnetic energy storage (SMES) systems.<sup>3</sup> An important consideration in designing such devices is the power dissipation in the superconducting coil. Power losses may originate from the motion of flux lines,<sup>4</sup> the hysteretic behavior of the magnetization,<sup>5</sup> and eddy currents.<sup>6</sup> The last two loss mechanisms are expected only if the system is operating in an ac mode. In a dc operation, however, losses due to flux motion only are expected. These dc losses are manifested by development of a dc voltage  $V_{dc}$  across the superconductor.

In this letter we investigate the response of a high  $T_c$  superconducting coil to an ac current  $I_{ac}$  superimposed on a bias dc current  $I_{dc}$ . Our results reveal a new phenomenon, namely the generation of an additional dc voltage  $\Delta V_{dc}$ , and consequently extra dc losses, induced by the ac current. The size of the effect is significant and depends on  $I_{dc}$ ,  $I_{ac}$ , and the frequency of the ac signal. A similar “dynamic resistance” phenomenon, accompanied by the generation of a dc voltage, was observed in low-temperature superconductors carrying a dc transport current and subjected to an applied ac field.<sup>7,8</sup> The dynamic resistance is explained within the Bean critical state model<sup>5</sup> as resulting from a net flow of flux across the superconductor during the ac cycle.<sup>7,8</sup> Our experiment is more complex since both the field and current have ac components. The above explanation based on the Bean model imparts a role only to the ac field in generating the dc voltage. Moreover, it is clear that the Bean model, without considering the giant flux creep<sup>4</sup> in HTS, cannot explain the observed current–voltage ( $I$ – $V$ ) curves in these materials. In this work we propose an alternative explanation to the generation of  $\Delta V_{dc}$  based on the nonlinear magnetoresistance of

the HTS coil. In our model, both the  $I$ – $V$  curve and the additional voltage  $\Delta V_{dc}$  due to the ac current have the same origin, namely the flux creep phenomenon. Moreover, in this model the ac current and the ac field associated with it both contribute to the generation of  $\Delta V_{dc}$ . We discuss the significance of this effect in power applications of HTS coils such as FCL<sup>9</sup> and SMES<sup>10</sup> designs in which ac current is superimposed on a dc bias current.

The HTS coil, purchased from American Superconductor Corporation, is made of 162 m multifilamentary silver-sheathed  $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10+\delta}$  tape, with a rectangular cross section of  $1.5 \text{ mm}^2$ . At 77 K it has an inductance of 17 mH and a critical current ( $1 \mu\text{V}/\text{cm}$  criterion) of 22.2 A, yielding a stored energy of 4.2 J. An ac signal, generated by amplifying a sine wave from a multifunction synthesizer, is coupled into the HTS coil using a 1:1 transformer. The relatively large alternating voltage generated across the coil is low-pass filtered in order to isolate its dc component.

Figure 1 shows typical  $I$ – $V$  curves of the HTS coil, at  $T = 77 \text{ K}$ , with and without ac current (200 mA rms, 205 Hz). As a result of the ac current, the  $I$ – $V$  curve is shifted upward, and the critical current is reduced from 22.2 to 21.7 A. Within the range of the experiment,  $I_{dc} = 16$ –22.5 A, the difference  $\Delta V_{dc}$  between the two curves increases linearly with  $I_{dc}$  (dotted curve in Fig. 1). Note the large size of the

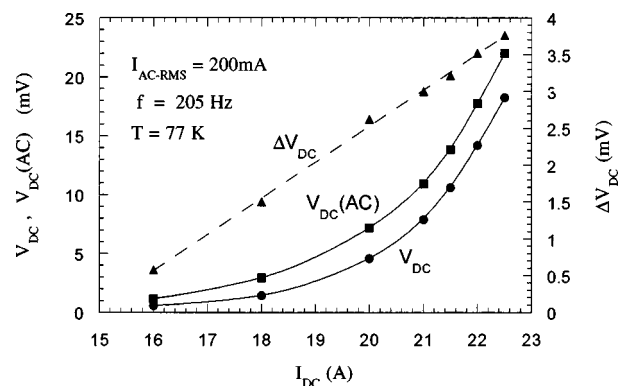


FIG. 1.  $I$ – $V$  curves of the HTS coil at  $T = 77 \text{ K}$ , with (squares) and without (circles) ac current (200 mA rms, 205 Hz). The dotted line shows the difference between these two  $I$ – $V$  curves.

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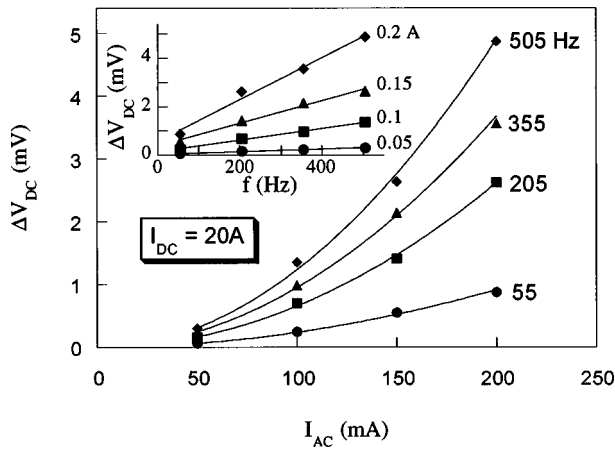


FIG. 2. Incremental dc voltage as a function of  $I_{ac}$  at constant  $I_{dc}$  (20 A) and different frequencies: (inset) incremental dc voltage as a function of frequency at constant  $I_{dc}$  (20 A) and different  $I_{ac}$ .

effect, e.g., for  $I_{dc} = 22$  A,  $\Delta V_{dc} = 3.5$  mV, i.e., an increase of more than 20% in  $V_{dc}$ .

Figure 2 shows the dependence of  $\Delta V_{dc}$  on the amplitude of the ac current, for various frequencies from 55 to 505 Hz. The solid lines show fits to a quadratic dependence  $\Delta V_{dc} \propto I_{ac}^2$ . The change  $\Delta V_{dc}$  in the dc voltage increases linearly with the frequency, as shown in the inset to Fig. 2 for various values of  $I_{ac}$  and a constant level of  $I_{dc} = 20$  A.

Clearly, the generation of a dc voltage by the alternating current is due to a nonlinear behavior of the HTS coil. We consider an equivalent circuit of the coil consisting of a pure inductance  $L$  in series with a resistance  $R$  (the "magnetoresistance" of the coil). When a dc current  $I_{dc}$  flows through the HTS coil it generates a dc voltage drop  $V_{dc} = I_{dc}R_{dc}$ , where  $R_{dc}$  is the magnetoresistance corresponding to the current  $I_{dc}$  and the self-field  $B_{dc}$  created by this current. When an additional alternating current  $I_{ac}(t)$  is superimposed on  $I_{dc}$ , the ac current and its associated self-field  $B_{ac}(t)$  modulate the magnetoresistance by adding a time varying contribution  $\Delta R(t)$ . It is important to note that  $\Delta R(t)$  is not a function of  $I_{ac}$  and  $B_{ac}$  alone, but it also depends on  $I_{dc}$  and  $B_{dc}$  as  $R$  is a nonlinear function of both current and field.<sup>11</sup> The flow of the ac and dc currents causes a voltage drop  $V(t)$  across the HTS coil:

$$V(t) = [I_{dc} + I_{ac}(t)][R_{dc} + \Delta R(t)] + d\phi/dt, \quad (1)$$

where  $\phi = L(I_{ac} + I_{dc})$  is the magnetic flux through the coil. We are interested in the dc voltage across the HTS coil which is given by the time average  $\langle V(t) \rangle$  of  $V(t)$ . Note that in the absence of a drift in  $\phi(t)$ , the average  $\langle d\phi/dt \rangle$  is identically zero because  $\phi$  changes periodically with time and therefore its time derivative has no dc component. However in HTS, because of magnetic relaxation,<sup>4</sup> the average of the magnetic flux in the superconductor decays approximately logarithmically with time, thus  $\langle d\phi/dt \rangle$  decays with time as  $1/t$ . Therefore, the dc (zero frequency) component contributed by  $d\phi/dt$  may be of significance only at short times after the ac signal is turned on. On the other hand, the average of the first term on the right hand side of Eq. (1) (the product of the two square brackets) contributes a steady dc component  $V_{dc} + \Delta V_{dc}$ , where

$$\Delta V_{dc} = I_{dc} \langle \Delta R \rangle + \langle I_{ac} \rangle R_{dc} + \langle I_{ac} \Delta R \rangle. \quad (2)$$

This general equation takes into account the possibility that  $I_{ac}(t)$  is nonsinusoidal, with a nonvanishing average. However, in our experimental setup  $\langle I_{ac} \rangle = 0$ , since  $I_{ac}$  is induced by ac coupling of the HTS coil to the ac source. Also note that the dc current through the coil is supplied by a constant current source, thus the dc current remains the same after application of the ac signal. Under these conditions, the balance of the dc voltages in the circuit yields:  $I_{dc}(R_{dc} + \langle \Delta R \rangle) \equiv V_{dc} + \Delta V_{dc}$ , or  $\Delta V_{dc} \equiv I_{dc} \langle \Delta R \rangle$ . Thus, we conclude that the increase in the dc voltage is mainly due to the average increase  $\langle \Delta R \rangle$  in the magnetoresistance of the HTS coil.

As mentioned above, the ac current induced into the HTS coil and the magnetic ac self-field associated with it modulate the coil's magnetoresistance  $R$ , giving rise to a nonvanishing  $\langle \Delta R \rangle$  because of the nonlinear dependence of  $R$  on current and field. Note that the nonlinearity of the  $R$ - $I$  curve, as deduced from the  $V$ - $I$  curve alone, cannot explain the large  $\langle \Delta R \rangle$  required to obtain the relatively large  $\langle \Delta V_{dc} \rangle$  observed in our experiment.<sup>12</sup> In the calculations of  $\langle \Delta R \rangle$  one should take into account hysteresis effects in  $R$  due to flux trapping<sup>13</sup> and surface barriers.<sup>14</sup> The large  $\langle \Delta V_{dc} \rangle$  observed in our experiment indicates that  $\Delta R$  traverses asymmetric minor hysteresis loops, giving rise to a relatively large  $\langle \Delta R \rangle$ . Calculation of  $\langle \Delta R \rangle$  requires a detailed knowledge of the flux creep mechanism and the irreversible magnetic behavior of the HTS coil under the experimental conditions. However, we may estimate the behavior of  $\langle \Delta R \rangle$  from our data. For example, from the dependence of  $\Delta V_{dc}$  upon  $I_{dc}$  (dotted line in Fig. 1) one can deduce that  $\langle \Delta R \rangle$  depends strongly on  $I_{dc}$ ; it vanishes below  $I_{dc} = 15$  A and increases from approximately 0.04 m $\Omega$  at 16 A to 0.16 m $\Omega$  at 22 A. The parabolic dependence of  $\Delta V_{dc}$  on  $I_{ac}$  (Fig. 2) can be interpreted as resulting from the parabolic dependence of the ac magnetic induction of the coil on the ac field<sup>5</sup> associated with  $I_{ac}$ . The linear dependence of  $\Delta V_{dc}$  on the frequency (inset to Fig. 2) is due to the fact that in order to maintain a constant ac current through the coil, the amplitude of the input voltage  $V(t)$  must be increased as the frequency is increased, because of the increase in the impedance of the HTS coil. As a result, all the harmonics of  $V(t)$ , as well as its dc component, increase accordingly. The increase in the dc component of the voltage while the current through the coil remains constant implies that  $\langle \Delta R \rangle$  increases with frequency. The discussion below suggests that this effect may be ascribed to relaxation phenomena causing an increase in the average flux line velocity with frequency.

The generation of the incremental dc voltage may be discussed on a microscopic level, using the equation  $E = Bv$ , relating the electric field  $E$  to the flux line velocity  $v$  (the voltage across the HTS coil is given by the integration of  $E$  along the coil wire). The induced ac current modulates the magnetic induction  $B$  in a nonlinear fashion and, as a result, the activation energy  $U$  for flux creep is also modulated as  $U$  depends nonlinearly on both the current and the magnetic induction.<sup>4</sup> Modulation of the activation energy causes modulation of the flux line velocity as both are related through the equation  $v = v_0 \exp(-U/kT)$ .<sup>4</sup> Denoting the time dependent changes in  $B$  and  $v$  by  $\Delta B$  and  $\Delta v$ , respectively, one obtains for the average increment  $\langle \Delta E \rangle$ :

$$\langle \Delta E \rangle = B \langle \Delta v \rangle + \langle \Delta B \rangle v + \langle \Delta B \Delta v \rangle. \quad (3)$$

The main contribution to  $\Delta E$  comes from the first two terms  $B \langle \Delta v \rangle$  and  $\langle \Delta B \rangle v$ . The first term results from enhanced flux creep due to the ac signal. The second results from flux trapping and surface barrier effects.<sup>14</sup> By this approach, the frequency dependence of  $\langle \Delta E \rangle$  may be ascribed to relaxation in  $E$  which proceeds as  $1/t$  (see Ref. 15) affecting the wave form of  $E$ . As the frequency increases, the effect of relaxation becomes less important in the time window of the experiment and as a result  $\langle \Delta E \rangle$  increases.

The importance of this study in power applications of HTS coils is demonstrated in SMES.<sup>10</sup> The power dissipation in the HTS coil is a substantial part of the overall losses determining the SMES efficiency. In a typical application of SMES, a superconducting coil serves as a buffer between the ac power line and the load, stabilizing the voltage and the frequency at the load. A persistent bias current  $I_{dc}$  flows in the coil, and the coil is “charged” and “discharged” with pulses of current  $\Delta I \ll I_{dc}$ , to compensate for short-term power fluctuations in the electric grid. This mode of operation is effectively equivalent to a superposition of  $I_{ac}$  on  $I_{dc}$ —the topic of this study. The dc voltage increment observed in this work produces an extra dc power loss. The results of this work are also applicable to various designs of FCL, where coupling to the ac line may provide an additional channel for energy loss.

In summary, alternating current in an HTS coil carrying dc current causes a significant increase in the coil dc voltage. We attribute this effect to the nonlinear change in magnetoresistance of the coil caused by the ac current and the self-magnetic field associated with it. The microscopic origin of this effect is the enhanced flux creep process caused by the application of the ac signal, as well as flux trapping and surface barrier effects. The superposition of ac and dc signals in HTS coils may appear in various power applications such

as SMES and FCL. The results of the present work may be important in the design of such devices.

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