Voltage response of current carrying Y–Ba–Cu–O tapes to alternating magnetic fields

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We present a study of the alternating voltage generated in $YBa_2Cu_3O_{7-\delta}$ (YBCO) tapes in response to sinusoidal magnetic fields applied perpendicular to the tapes. The alternating field induces a strongly nonlinear voltage response with various waveforms that drastically change upon changing the bias current, the bias magnetic field, and the amplitude and frequency of the alternating field. In particular, one observes transitions from waveforms including double peaks to waveforms including a single peak in one cycle of the alternating field. We attribute these effects to modulation of the vortex pinning energy by both the alternating magnetic field and the alternating current induced by it. Our model allows separation of these two contributions to the total response, thus revealing the dominating source of the nonlinear response and its accompanied steady component at different experimental conditions. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3125318]

I. INTRODUCTION

The advent of power devices based on high-T_c superconductors has triggered renewed interest in effects of alternating magnetic fields on transport properties of superconducting strips and wires.[1–16] Attention has been mainly focused on a particular phenomenon, namely, the generation of a steady electric field by the alternating magnetic field. This phenomenon has been observed experimentally[1–3,5–12] and analyzed theoretically in several previous studies.[1,2,4,9,13] According to these studies, the applied alternating magnetic field modulates the vortex spatial distribution inside the superconducting sample, giving rise to a net flow of vortices from one side of the sample to the other. This process is demonstrated in Fig. 1, based on the Bean model.[17] The lowest profile in Fig. 1(a) describes the steady state induction distribution at the beginning of an ascending branch of the ac field. This asymmetrical profile results from the field induced by the dc transport current through the sample, in addition to the applied dc and ac fields. While the ac field increases, the induction profiles evolve as described in Fig. 1(a), causing a net flux flow in the indicated direction dictated by the direction of the transport current through the sample. As the ac field decreases, the flux profiles evolve as described in Fig. 1(b), giving rise to a net flux flow in the *same* direction. Taking into account the amount of flux moving at each stage of the ac magnetic field, one finds that the induced electric field exhibits two peaks in one cycle of the ac field, appearing when the ac field changes at a maximum rate [see Fig. 1(c)]. This model, referred to as the "dynamic resistance" model, explains well the generation of a steady electric field by the alternating magnetic field in a regime where flux creep effects can be neglected. In the general case, the alternating field also modulates the vortex pinning energy $U(j,B)$ which depends on both the current density j and the magnetic induction B. Thus, a complete analysis of the voltage response of superconductors to alternating magnetic fields must take into account modulation by the field of both the vortex spatial distribution as well as the vortex pinning energy.

In this paper we concentrate on the latter effect and study it under special experimental conditions where the

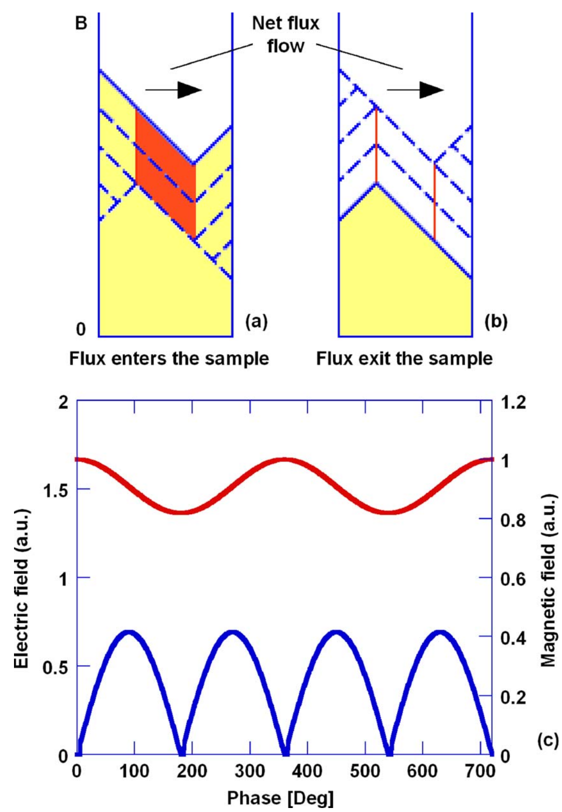

FIG. 1. (Color online) Distribution of magnetic induction in current carrying slab during ascending (a) and descending (b) branches of external alternating magnetic field [after Andrianov *et al.* (Ref. 1)]. (c) Calculated voltage response according to the dynamic resistance model. The top part of the figure represents the applied external magnetic field, while the lower part represents the voltage response created by the vortex motion.

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modulation of U dominates the voltage response. This is achieved by subjecting the sample to a steady magnetic bias field much larger than the alternating field and by transmitting through it current which is close to the critical current, biasing its voltage response to the flux creep regime. We observe and analyze various waveforms that drastically change upon changing the bias current, the bias magnetic field, and the amplitude and frequency of the alternating field. In particular, we observe waveforms including a single peak in one cycle of the alternating field, in contrast to the double peak response predicted by the dynamic resistance model. Our theoretical analysis takes into account modulation of the vortex pinning energy by both the alternating magnetic field and the alternating current induced by it. Moreover, our analysis allows separation of these two contributions to the total alternating response, thus revealing the dominating source of the nonlinear voltage response and its accompanied steady component.

II. EXPERIMENTAL TECHNIQUE

Measurements were performed on second generation industrial $YBa_2Cu_3O_{7-\delta}$ (YBCO) tapes (cross section of 4.35 $\times 0.2$ mm) manufactured by American Superconductors Corporation (AMSC), using the Metal Organic Deposition/Rolling-Assisted Biaxially Textured Substrate (MOD/RABITS™) process.[18] The tapes consisted of a 1 μm thick YBCO layer deposited on a ferromagnetic Ni–5%W substrate. A homogeneous magnetic field was generated by racetrack copper coils, as described in Ref. 19. The coils and the measured tape were immersed in liquid nitrogen ensuring both homogenous and constant temperature of $\sim$77 K. Measurements described in this paper were performed on a tape of length of 10 cm carrying controllable dc transport current and exposed to combined dc and ac magnetic fields: $H=H_{dc}+h_{ac}\sin(\omega t)$, both directed perpendicular to the tape plane. The *V-I* curves were measured using 8.5 digits, 1271 Datron DVM. The time dependent voltage response was measured using Tektronix-420A digital scope with differential preamplifier ADA400A. The electric field E along the tape was calculated as the ratio between the measured voltage and the length between the measurement leads. The voltage induced in the measurement loop by the ac magnetic field was reduced to minimum by minimizing the area enclosed by the loop.

III. EXPERIMENTAL RESULTS

The basic phenomenon of generation of a steady electric field by the alternating magnetic field is demonstrated in Fig. 2. The solid curve shows the *E-I* curve measured in a sample subjected to a steady field of 700 Oe. Using the 1 μV/cm criterion, one obtains a critical current $I_c \simeq 73$ A. Superimposing a sinusoidal field of amplitude of 200 Oe and frequency of 15 Hz on the steady field causes a significant increment in the measured dc electric field and drastically reduces the critical current to a value of 30 A, as shown by the dashed curve in Fig. 2. To obtain an insight into the physical origin of this effect, we measured the waveform of the electric field $E(t)$ generated along the sample in response

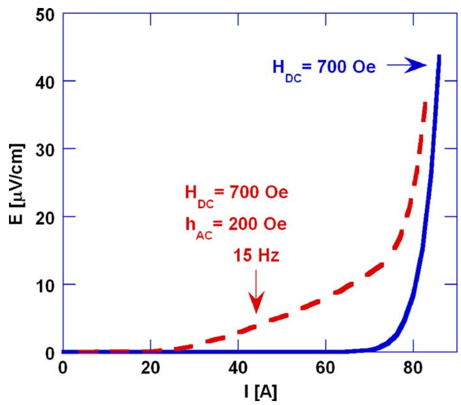

FIG. 2. (Color online) *E-I* curve measured in a sample subjected to a steady field of 700 Oe (solid curve). The dashed curve shows the effect of adding an alternating field of amplitude of 200 Oe and frequency of 15 Hz.

to the sinusoidal magnetic field for bias dc currents ranging from 40 to 85 A. The results, presented in Fig. 3, demonstrate a transition from waveforms with double peaks in one cycle of the alternating magnetic field for low bias currents to waveforms with a single peak for high bias currents. Note that the double peaks appear approximately when the ac field changes at the highest rate, whereas the single peak response is approximately in phase with the ac field. As will be discussed later, while the double peak response is a characteristic of the dynamic resistance effect, the single peak response indicates domination of flux creep effects.

A similar phenomenon of transition from double peak to a single peak response, and vice versa, is observed when changing other parameters such as the dc magnetic field, the frequency, or the amplitude of the ac magnetic field. Figure 4 shows the response of a sample carrying a constant current of 82 A to a sinusoidal field of amplitude of 200 Oe and frequency of 15 Hz, when the sample is biased by different dc fields. One clearly see that the response gradually transforms from a double peak to a single peak waveform in one cycle of the ac field as the bias field increases from 0 to 800 Oe. Figures 5(a) and 5(b) demonstrate the opposite transition from a waveform with a single peak to a waveform with double peak in one cycle of the ac field. In these experi-

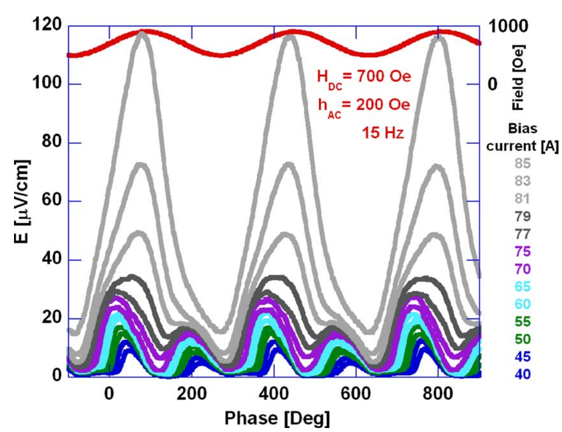

FIG. 3. (Color online) Waveforms of electric fields generated in response to sinusoidal magnetic field of amplitude of 200 Oe and frequency of 15 Hz. The dc magnetic field is 700 Oe and the transport current varies in the range of 40–85 A. The upper curve describes the applied alternating field.

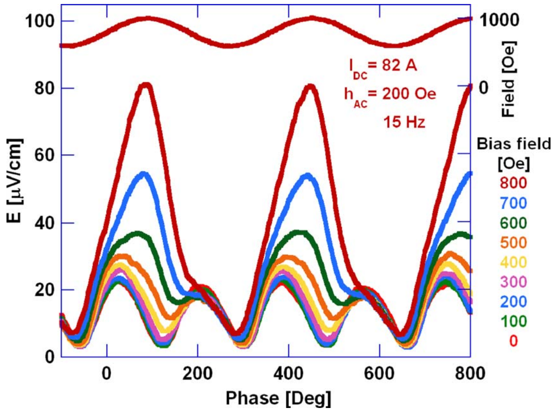

FIG. 4. (Color online) Waveforms of electric field generated in a sample carrying steady current of 82 A in response to sinusoidal magnetic field of amplitude of 200 Oe and frequency of 15 Hz. The dc magnetic field is varied from 0 to 800 Oe.

ments, we set conditions in which the ac response oscillates approximately in phase with the ac field, exhibiting a single peak in one cycle [lower curves in Figs. 5(a) and 5(b)]. A second peak starts to develop by increasing either the amplitude or the frequency of the sinusoidal magnetic field, as shown by the upper curves in Figs. 5(a) and 5(b).

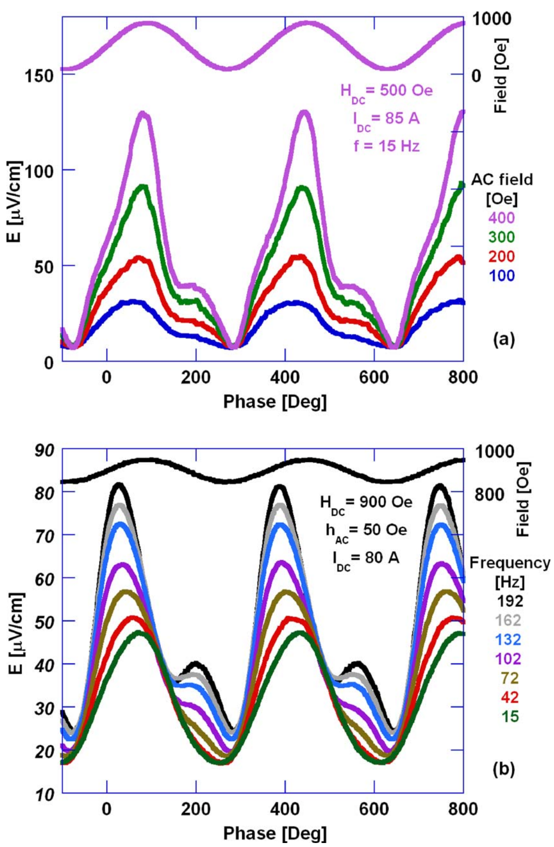

FIG. 5. (Color online) (a) Waveforms of electric field generated in a sample in response to sinusoidal magnetic fields of the same frequency (15 Hz) and different amplitudes. The sample carries steady current of 85 A and subjected to a steady field of 500 Oe. The amplitude of the sinusoidal magnetic field is varied between 100 and 400 Oe. (b) Response to sinusoidal magnetic fields of the same amplitude (50 Oe) and different frequencies. The sample carries steady current of 80 A and subjected to a steady field of 900 Oe. The frequency of the sinusoidal magnetic field is varied between 15 and 192 Hz.

IV. DISCUSSION

The alternating magnetic field generates alternating voltage response via both mechanisms: (a) modulation of the vortex spatial distribution within the sample, giving rise to "dynamic resistance," and (b) modulation of the vortex pinning energy affecting the vortex creep. A transition from a regime where the first mechanism dominates to a regime where the second one dominates can be obtained by changing the dc bias current, dc magnetic field, as well as the amplitude and frequency of the ac field.

The dynamic resistance model has been discussed previously in detail,[1,2,4,9,13] predicting two peaks in the voltage response in one cycle of the ac field. Experimentally, we observe a double peak response, similar to that described in Fig. 1(c), under conditions where the pinning energy is high and its modulation by the ac field is insignificant, e.g., when the bias current is much smaller than the critical current ($\simeq$73 A) as shown by the lowest curves in Fig. 3.

In the following we show that the single peak response obtained in our experiments can be explained as resulting from modulation of the vortex pinning energy $U(j,B)$ by the ac magnetic field. Assuming that the dc induction B_{dc} is much larger than the time dependent ac induction B_{ac} and that the dc transport current density j_{dc} is much larger than the induced ac current density j_{ac}, the time dependence of the activation energy U can be estimated as follows:

$$U(j_{dc}+j_{ac},B_{dc}+B_{ac}) = U(j_{dc},B_{dc}) + \left(\frac{\partial U}{\partial j}\right)_{j_{dc}} j_{ac} + \left(\frac{\partial U}{\partial B}\right)_{B_{dc}} B_{ac}. \quad (1)$$

The electric field E due to flux creep is related to the pinning energy by[20]

$$E = E_0 e^{-U(j,B)/KT}, \quad (2)$$

where the electric field E_0 at $j=j_c$ is assumed to be constant and K and T are the Boltzman constant and temperature, respectively. Combining Eqs. (1) and (2), one obtains

$$E(t) = E_0 e^{-U(j_{dc},B_{dc})/KT} e^{-(1/KT)(\partial U/\partial j)_{j_{dc}} j_{ac}(t)} \times e^{-(1/KT)(\partial U/\partial B)_{B_{dc}} B_{ac}(t)}. \quad (3)$$

According to Eq. (3), $E(t)$ is a product of three terms: A constant term $E_{dc}=E_0 e^{-U(j_{dc},B_{dc})/KT}$ determined by the dc current and the dc magnetic field, and two oscillating terms, $E_B=e^{-(1/KT)(\partial U/\partial B)_{B_{dc}} B_{ac}(t)}$ and $E_J=e^{-(1/KT)(\partial U/\partial j)_{j_{dc}} j_{ac}(t)}$ associated with the oscillating magnetic induction $B_{ac}(t)$ and the oscillating current $j_{ac}(t)$ induced by it. Since $(\partial U/\partial j)_{j_{dc}}$ continuously decreases as j_{dc} increases, the relative contribution of the induced ac current can be reduced by increasing the bias current j_{dc}. Thus, if j_{dc} is sufficiently large, the oscillating term E_B will dominate the ac response, creating a waveform $E(t)$ oscillating in phase with the field $B_{ac}(t)$, thus exhibiting a single peak in one cycle of $B_{ac}(t)$. The transition from a double peak response to a single peak response with increasing bias current described in Fig. 3 can thus be interpreted as follows: For low bias currents the effect of vortex creep is weak and the ac response mainly results from modulation of the vortex distribution, giving rise to two peaks located approximately at times where the rate of change of the ac field is maximum (see lower curves in Fig. 3). As the bias current increases, modulation of the vortex creep due to modulation of U by both the ac field and the ac current induced by it becomes more and more significant. The waveform obtained in this regime is characterized by two asymmetrical peaks, as shown by the middle curves of Fig. 3. For bias currents near the critical current, modulation of U by the ac field dominates the ac response, giving rise to a single peak oscillating in phase with $B_{\mathrm{ac}}(t)$ (upper curve in Fig. 3).

Transition from a regime where modulation of the vortex distribution dominates to a regime where modulation of vortex creep dominates can also be achieved by increasing the dc bias field, as demonstrated in Fig. 4. As the bias field increases, the critical current decreases and the effect of flux creep becomes more significant. When the critical current is reduced to a value in the vicinity of the bias dc current, modulation of U by the ac field dominates the response and a waveform with a single peak in a cycle is obtained. The opposite transition from a single peak to a double peak response, by increasing the amplitude or the frequency of the ac field [see Figs. 5(a) and 5(b)] can be explained as follows. The single peak response, oscillating approximately in phase with $B_{\mathrm{ac}}(t)$, indicates that modulation of U by $B_{\mathrm{ac}}(t)$ dominates the response. As the amplitude of the ac field increases, modulation of the vortex distribution becomes more significant and the double peak response associated with it becomes evident. Similarly, as the frequency of the ac field increases, flux enters and leaves the sample at a higher rate, giving rise to larger contribution of the dynamic resistance effect to the total response.

As stated above, as long as $j_{\mathrm{ac}} \ll j_{\mathrm{dc}}$ and $B_{\mathrm{ac}} \ll B_{\mathrm{dc}}$, the oscillating part of $E(t)$, due to flux creep, can be expressed as a product of two oscillating terms, E_B and E_J, associated with the oscillating magnetic induction $B_{\mathrm{ac}}(t)$ and the oscillating current density $j_{\mathrm{ac}}(t)$ induced by it, respectively. In the following we show that these two oscillating terms can be isolated, allowing examining the contribution of $B_{\mathrm{ac}}(t)$ and $j_{\mathrm{ac}}(t)$ to the total response separately. These contributions depend on the partial derivatives $(\partial U/\partial B)_{B_{\mathrm{dc}}}$ and $(\partial U/\partial j)_{j_{\mathrm{dc}}}$, respectively. Since U depends on the absolute values of j and B, these derivatives change sign when the direction of j_{dc} or that of B_{dc} is reversed, leading to a change in the exponent sign of the corresponding terms. Thus, one can separate between the different terms of Eq. (3) by simply multiplying two waveforms corresponding to opposite bias fields or current directions. This is demonstrated in Fig. 6 which presents three measured waveforms with different directions of current and bias field. In Fig. 6(a) the field and current were applied along certain directions. In Fig. 6(b) the directions of both the field and the current were reversed, and in Fig. 6(c) only the field direction was reversed.

According to Eq. (3), we can isolate the dc term E_{dc}, by multiplying the waveform of Fig. 6(a) with that of Fig. 6(b) and taking the square root of the product. The results are described in Fig. 7 for different bias currents. One can see that for high bias currents, where the contribution of the creep modulation dominates, the obtained waveform is al-

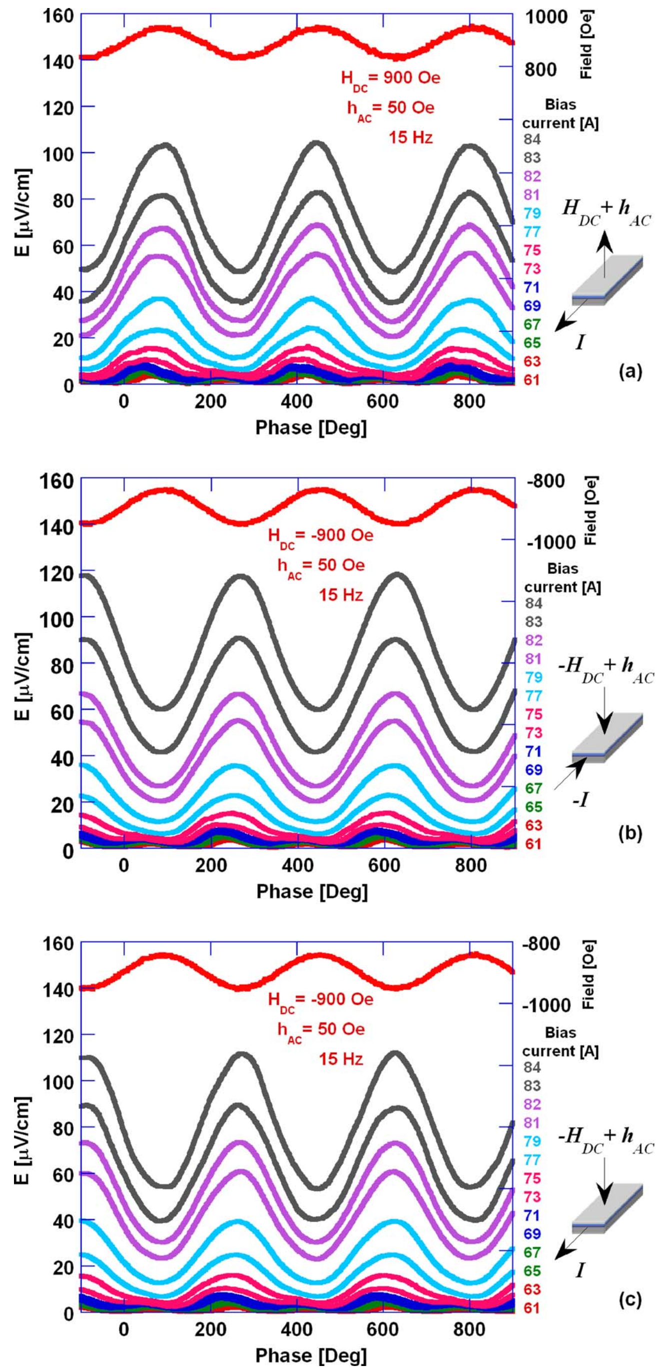

FIG. 6. (Color online) (a) Electric field waveforms generated in response to ac field of amplitude of 50 Oe and frequency of 15 Hz, measured for different dc bias currents ranging from 61 to 84 A. The dc bias field is 900 Oe. (b) Same as (a) with reversed directions of bias field and bias current. (c) The same measurement as described in (a), however, here we reverse the direction of the dc magnetic field. The directions of the field and the current are sketched for (a)–(c).

most time independent. Moreover, the average of this waveform yields exactly the dc voltage obtained from the conventional *E-I* measurements (see Fig. 8). Deviations of the *E-I* curve calculated in this way from the dc measured *E-I* curve occurs only for low currents where the contribution of the dynamic resistance effect becomes significant.

One can further isolate the contributions of the ac field and the current induced by it by taking the square root of the product of the waveforms corresponding to opposite bias

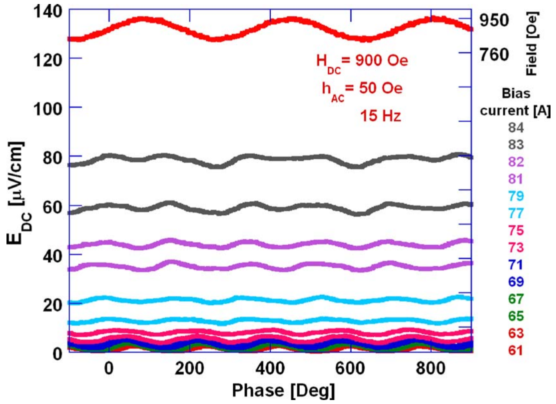

FIG. 7. (Color online) dc component of the response, calculated as the square root of the product of the waveforms in Fig. 6(a) and 6(b).

currents [Figs. 6(b) and 6(c)] and opposite bias fields [Figs. 6(a) and 6(c)], respectively. The results are presented in Figs. 9(a) and 9(b), respectively. One can see that the modulation depth of the current term is much smaller than that of the field term, and that it further decreases with increasing the bias current. This is expected since $(\partial U/\partial j)_{j_{\mathrm{dc}}}$ decreases as j_{dc} increases. Domination of the field term gives rise to a response which oscillates in-phase with the ac field as discussed above.

V. SUMMARY AND CONCLUSIONS

The voltage response of current biased superconducting tapes to sinusoidal magnetic fields originate from both (a) modulation of the vortex spatial distribution within the sample[1,2,4,9,13] and (b) modulation of the vortex pinning energy. The first mechanism dominates when the sample is biased to a regime where the pinning energy is relatively large, (i.e., $I_{\mathrm{dc}} \ll I_c$), and its modulation by the alternating field is insignificant. The second mechanism can dominate when the sample is biased to the flux creep regime (i.e., $I_{\mathrm{dc}} \simeq I_c$), where small changes in the pinning energy largely affect the flux motion. A transition from a regime where the first mechanism dominates to a regime where the second one dominates can be obtained by increasing the bias current or the bias magnetic field. Conversely, the opposite transition can be obtained by increasing the amplitude and/or the frequency of the ac field. These transitions are manifested by a change in the waveform of the alternating response to sinusoidal field from double peak to a single peak response, and vice versa, respectively.

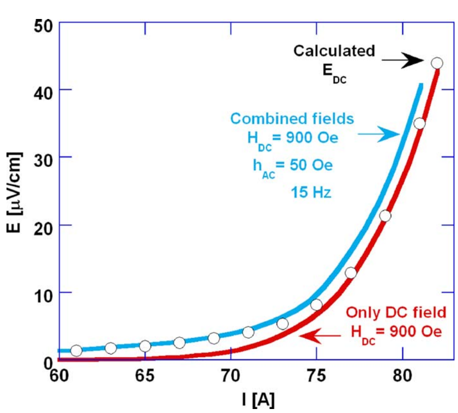

FIG. 8. (Color online) *E-I* curves measured by the conventional dc method (solid lines) with and without ac field. Circles indicate *E-I* curve calculated as the average of the waveforms described in Fig. 7.

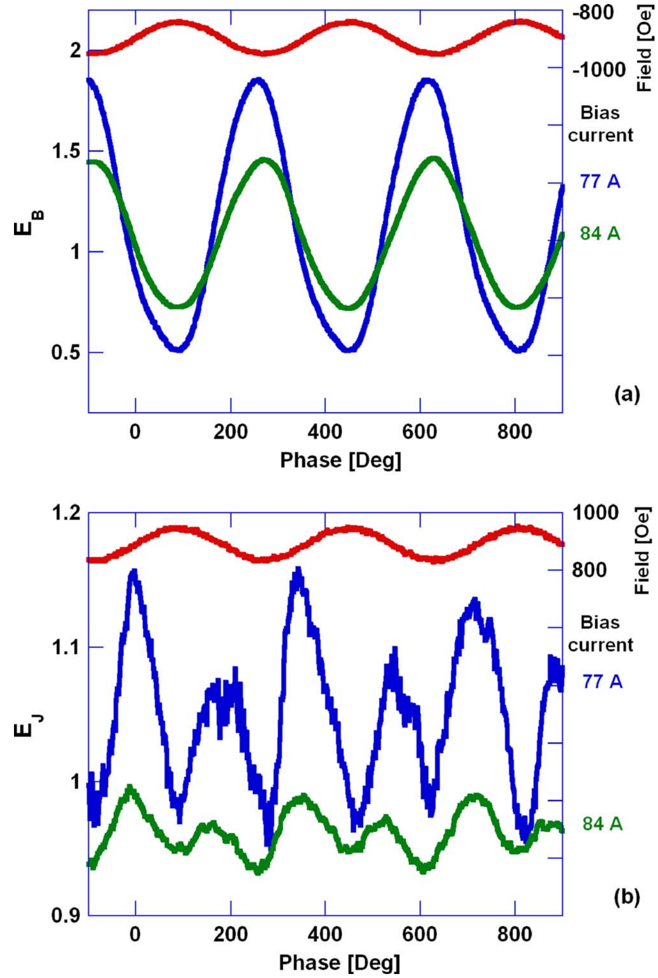

FIG. 9. (Color online) Calculated contributions the ac field (a) and the current induced by the ac field (b) to the total response for bias currents of 77 and 84 A.

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