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AC-induced DC voltage in HTS coil

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Abstract

The interplay between AC and DC currents in a High-T_c Superconducting (HTS) coil, made of multifilamentary silver-sheathed Bi-2223 tape, was investigated. We observed that the application of a small sinusoidal current in the frequency range of 50–500 Hz into the coil, while it is already carrying a DC current in the range of 16–22.5 A, caused an increase in the coil DC voltage. The DC voltage increment due to the AC signal is found to increase linearly with frequency and quadratically with amplitude. The DC voltage increment increases as the coil current grows towards its critical value of 22.2 A. This result may be important in some power applications such as fault current limiters (FCL) and superconducting magnet energy storage (SMES) based on HTS coils. © 1998 Elsevier Science B.V. All rights reserved.

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1. Introduction

The recent progress in manufacturing multifilamentary silver-sheathed Bi-2223 (BSCCO) superconducting tapes has resulted in relatively long tapes with improved electrical and mechanical characteristics. This progress has enabled the fabrication of induction coils, based on high-T_c superconductors (HTS), which were used for the construction of prototype power devices such as transformers, motors, generators, fault current limiters (FCL) and superconducting magnetic energy storage (SMES) systems. An important consideration in designing such devices is the power dissipation in the superconducting coils. Depending on the wire structure and operating conditions such as temperature, magnetic field and current waveform, the power dissipation may include DC loss due to thermally activated flux creep in the presence of pinning centers [1], hysteresis loss [2,3] in the BSCCO filaments and AC eddy current and coupling losses [2–4]. AC power losses were measured with either calorimetric, transport or magnetic methods [5,6]. DC losses which depend on the DC current I and the voltage V are easily determined from the I–V curves.

In this work we study the influence of alternating current on the I–V curves of HTS coils. Measurements were done on a ring shaped HTS coil immersed in liquid nitrogen. We find that the applica-

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tion of alternating current to the HTS coil enhances the flux creep in the BSCCO filaments, resulting in additional DC voltage on the coil, and an increase of the power dissipated in its windings. This effect may be important in some power applications of high-T_c superconducting coils such as SMES and FCL.

2. Experimental method

A ring-shaped HTS coil purchased from American Superconductor (ASC) was used in our investigation. It is composed of 3 double pancakes placed one on top of the other and connected electrically in series. Each pancake is made of a 54 m long multifilamentary double tape with a cross section area of about 1.5 mm^2. At 77 K the coil has an inductance of 17 mH and a critical current (1 μV/cm criterion) of 22.2 A, yielding a stored energy of 4.2 J. The AC current, obtained by amplifying a sinewave generated by a multifunction synthesizer, was introduced into the coil by either a transformer or a direct coupling. In the transformer configuration two copper coils of 100 turns each are closely fitted one inside the other, forming an ‘air core’ transformer that couples the AC current passed through the primary winding into the secondary winding which is connected in series with the HTS coil. In order to elucidate the specific role of AC current the measurement procedure was repeated for a ‘direct coupling’ method in which AC current is directly coupled into the HTS coil with a closely fitted copper induction coil.

All coils are immersed in liquid nitrogen in nonmetallic containers. The coupling transformer is placed in a separate container in order to avoid the direct coupling of AC magnetic field into the HTS coil. The AC inductive voltage on the HTS coil is relatively large. In order to obtain a DC voltage measurement with a standard DVM, we used a low pass filter (LPF).

3. Results and discussion

As shown in Fig. 1, the measured DC voltage of the HTS coil is significantly increased when a sinusoidal current of 200 mA and 205 Hz is induced into the coil. This AC current also reduces the critical current from 22.2 A to 21.7 A. The dotted line in Fig. 1 shows the DC voltage increment ΔV due to the AC coupling, $\Delta V \equiv V_{DC}(AC) - V_{DC}$, where V_{DC} is the measured DC voltage on the HTS coil at a specific DC current level I_{DC}, and $V_{DC}(AC)$ is the voltage measured for a specified AC current superimposed on the same DC level. The I–V curve of Fig. 1 can be approximated as

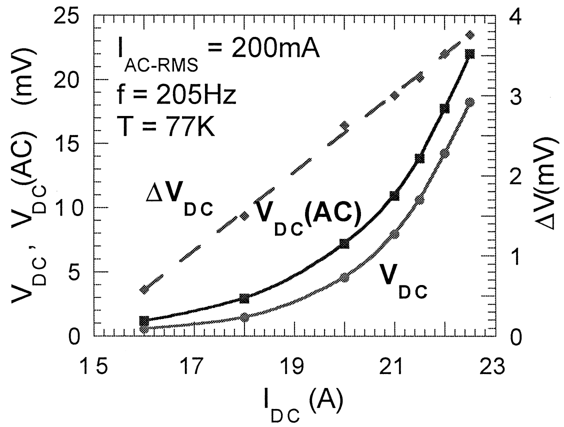

Fig. 1. I–V curves of the HTS coil without AC and with a presence of an AC of 200 mA. The dashed curve represents the difference ΔV between both curves.

$$V_{DC} = V_0 (I_{DC}/I_C)^n \quad (1)$$

where n is a temperature dependent power exponent, I_C is the coil critical current determined by the average electric field criterion $E_O = 1$ μV/cm and V_O is the voltage drop on the HTS coil at the critical current. Note that $V_0 = E_0 l$, where l is the total length of the wire used for winding the HTS coil. For a total wire length of 162 m we get 16.2 mV. Locating this value on the I–V curve obtained at 77 K yields the HTS coil critical current of 22.2 A as already stated. The power law fit of this curve yields.

The dependence of ΔV on the DC current level (I_{DC}) and on the sinusoidal current amplitude (I_{AC}) and frequency (f) was studied. We observe an increment in the DC voltage only when the DC current exceeds a certain level, in our case about 70% of I_C. For the DC current range 16–22.5 A it was found that ΔV increases monotonically with I_{DC}. As shown

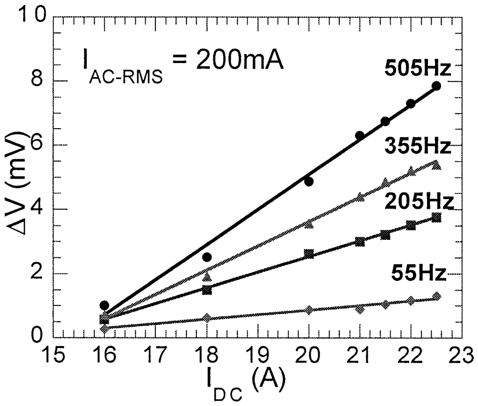

Fig. 2. The dependence of ΔV on the DC level (I_{DC}) for AC of 200 mA at different frequencies.

in Fig. 2, a roughly linear dependence is obtained for different AC frequencies 55, 205, 355 and 505 Hz and amplitude of 200 mA rms. The dependence of ΔV on the AC amplitude I_{AC} for the same frequencies and DC current level of 20 A is shown in Fig. 3. Curve fitting of these data, and others made at 18 and 22 A DC levels, yields power law dependence with an exponent between 1.7 and 2. As shown in Fig. 4, for the frequency region below 500 Hz, keeping I_{DC} and I_{AC} constant, ΔV increases linearly with the AC frequency.

The value of ΔV obtained with the 'direct coupling' method was about 3 times larger than that obtained with the 'transformer coupling' method at the same conditions of DC current level and sinusoidal current amplitude and frequency. An example is given in Fig. 5, where the frequency dependence of ΔV, as obtained by both methods, is compared for DC current level of 20 A accompanied by an alternating component of 100 mA. The larger response obtained with the 'direct coupling' method is explained by the presence of a 'coupled' AC magnetic field induced by the AC current in the copper coil in addition to the 'self' field induced by the AC current in the HTS coil. The superposition of the 'self' and 'coupled' fields presents the real field distribution around both coils in the coupling setup. The computation of radial component of magnetic induction B_R for both cases with 'PC-OPERA' (a software of Vector Fields for electromagnetic design) shows substantially higher values of B_R over the HTS coil cross section for the 'direct coupling' configuration, where the maximal value is approximately 3 times higher than for the 'transformer coupling'. Therefore, it is understood that the DC voltage increment ΔV is primarily induced by the c axis component of the AC magnetic field. In the 'transformer coupling' method a downwards deviation from the linear response is obtained above 500 Hz due to current redistribution in the silver sheath. A downwards deviation from the linear response in the 'direct coupling' method obtained at about 200 Hz (see Fig. 5) is explained by a reduction of the 'coupled' field part with respect to the 'self' field part due to the stronger current coupling at higher frequencies.

The DC voltage increment in the HTS coil is caused by its nonlinear behavior. A simple source of non-linearity is the form of the I–V curve. The relative voltage increment that can be derived from it (for $I_{AC} \ll I_{DC}$) is

$$\frac{\Delta V}{V} = \frac{n(n-1)}{4} \left(\frac{I_{AC}}{I_{DC}} \right)^2. \qquad (2)$$

Eq. (2) yields much lower values as compared with the experimental results. Moreover it is frequency independent while the experimental results exhibit a linear increase with frequency. For example, when the DC current in the HTS coil 18 A is superimposed with 100 mA AC current, Eq. (2) yields a ratio $\Delta V/V$ of 0.21%, while the measured ratio is about two orders of magnitude higher, lin-

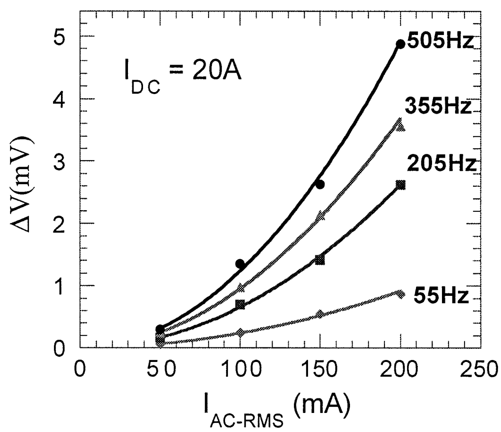

Fig. 3. The dependence of ΔV on the AC amplitude for fixed DC at different AC frequencies.

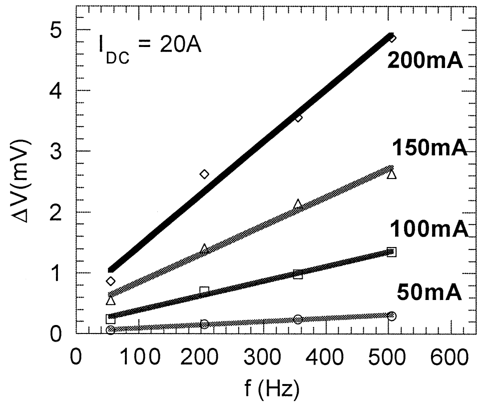

Fig. 4. The dependence of ΔV on the AC frequency (f) for fixed DC at different AC amplitudes.

early increasing with frequency from 12% at 55 Hz to 49% at 505 Hz.

The observed phenomena might be caused by the enhancement of flux creep in the HTS filaments. In order to understand the generation of incremental DC voltage discussed above, on a microscopic level, we use the equation $E=Bv$ relating the electric field E to the magnetic induction B and 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 non-linear fashion and, as a result, the activation energy U for flux creep [1] is also modulated as U depends nonlinearly on both the current and the magnetic induction. Modulation of the activation energy causes modulation of the flux line velocity as both are related through the equation [1]

$$v=v_0\exp(-U/kT). \quad (3)$$

Denoting the time dependent changes in B and v by ΔB and Δv, respectively, one obtains for the average increment $\langle \Delta E\rangle$:

$$\langle \Delta E\rangle = B\langle \Delta v\rangle + \langle \Delta B\rangle v + \langle \Delta B \Delta v\rangle. \quad (4)$$

The main contribution to ΔE 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 one results from flux trapping and surface barrier effects. The detailed analysis of the experimental results presents a severe problem because of non-uniformity of the electric field along the winding. Two reasons of this non-uniformity are the non-uniform distribution of the magnetic induction on the winding turns and the natural inhomogeneity of the superconducting wire.

The power dissipation in the HTS coil may be a substantial part of the overall losses, which determine system efficiency. The DC voltage increment observed in this work produces extra DC power losses $\Delta P = I_{DC}\Delta V$.

It is a common practice to reduce the operating DC current level of the HTS coil somewhat below its critical current I_C in order to reduce the coil DC voltage and the accompanying DC power dissipated. In this case one should consider the extra DC power loss due to AC application that may be comparable to the 'pure' DC power loss. By inspection of our results some guidelines can be drawn in order to reduce the relative increase of the DC power loss of HTS coils used in power applications where alternating current/field act on the winding carrying DC current. A simple approach, that can be implemented, for example in HT-SMES devices, in order to improve their electrical efficiency, is to increase the AC current frequency up to the eddy current limit at the expense of reducing its amplitude in the same proportion. This may be accomplished by appropriately adapting the response time of the device loop control. In some types of HTS coil based Fault-Current Limiters (FCL), such as the 'saturated magnetic core', 'bridge' and 'shunt' [7] extra DC power loss is similarly expected due to coupling of

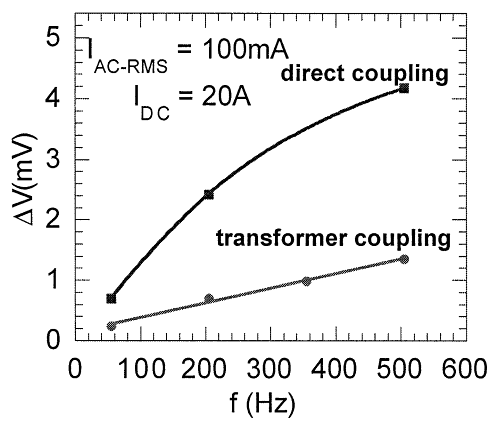

Fig. 5. ΔV as obtained by the 'transformer coupling' and 'direct coupling' methods for fixed DC at AC level of 100 mA at different frequencies.

the AC line current onto the DC current flowing in the HTS coil.

4. Summary

We have observed that the application of an alternating current into an HTS coil carrying DC current causes a significant increase in the coil DC voltage. It has been found that the DC voltage increment due to the sinusoidal current application increases linearly with the AC frequency and quadratically with its amplitude. This increment can be observed only when DC current exceeds a definite level and increase linearly with increase in current. This effect might be caused by the enhancement of flux creep in the HTS filaments due to the application of the AC current and the self magnetic field associated with it. 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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