AC Magnetization Loss Characteristics of HTS Striated Coated Conductors with Magnetic Substrates

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Abstract. AC magnetization losses in subdivided CC (Coated Conductor) with magnetic substrate were experimentally investigated comparing with those in subdivided CC with non-magnetic substrate for an AC external magnetic field perpendicular to the wide face of the CC. It is well known that the subdivision is effective to reduce magnetization losses in CC with non-magnetic substrate. The experimental results show that the subdivision is also effective for the CC with magnetic substrate and that the level of reduction of the losses by the subdivisions is almost the same as that of non-magnetic substrate CCs. It is concluded from the experimental results that the magnetic property of the substrate does not affect the magnetization losses in the subdivided conductor in the range of the experiment where the amplitude of the AC external magnetic field is 0 ~ 0.1 T and the frequency is 16 ~ 86 Hz.

1. Introduction
AC losses in HTS conductors are main losses in HTS AC power applications, such as HTS power cables, transformers and fault current limiters, and directly affect efficiency and economic feasibility of those AC power applications. Therefore, reduction of AC losses in conductors is essential to the AC power applications.

HTS coated conductors (CCs) with magnetic Ni-alloy substrates have high potentials as low-cost and long-length conductors, because the Ni-alloy is well-texturized by simple processes, and are expected to be promising conductors for AC power applications. However, the AC losses may be affected to increase by the magnetic property of the substrate. Actually, it was experimentally shown that the transport current losses in conductors with magnetic substrates are higher by an order of magnitude than those in HTS CCs with non-magnetic substrates [1], [2]. It is also shown that AC magnetization losses are dominated by the magnetic hysteresis losses in the substrates when an AC external magnetic field parallel to the wide face of the conductor [3]. Generally, AC magnetization losses due to the AC external magnetic field perpendicular to the wide face of the conductor are much larger than the transport current losses and the magnetization losses due to the parallel external magnetic field. Therefore, reduction of the magnetization losses due to the perpendicular magnetic field is important. It is widely known that striation of the superconductor layer is effective to reduce the AC magnetization loss due to the perpendicular magnetic field. In this paper, reduction of the magnetization losses in the magnetic substrate CCs by the striation is experimentally investigated comparing with that of non-magnetic substrate CCs.

2. Experimental
2.1. Measurement method of magnetization losses
The magnetization losses of the samples were measured by a dual in-plane pick-up coil method applying AC magnetic field perpendicular to the wide face of the conductor [4]. The dual pick-up coils consist of inner and outer in-plane pick-up coils which are differentially connected. The lengths of the both coils $L$ are the same and the numbers of turns and widths of the inner and outer pick-up coils are $n_{in}$ and $n_{out}$, and $w_{in}$ and $w_{out}$, respectively. They are so selected as $n_{in}w_{in} = n_{out}w_{out}$ to cancel the inductive voltage components of the dual pick-up coils induced by the external AC magnetic field. Actually, the inductive voltage components in the dual pick-up coils were greatly reduced by this arrangement, so that there was no need to use a cancel coil. However, cancellation of the stray losses was necessary and was done by use of a magnetic field detection-coil placed in the external AC magnetic field apart from the sample.

2.2. Samples
HoBCO CC tape with magnetic substrate [5] was used in this work. The parameters of the initial, non-striated conductor are given in table 1. The sample tape was successively striated to 2 and 4 filaments, following critical current and AC magnetization losses measurements at each stage of subdivision. For a filament patterning a standard photolithography and wet chemical etching techniques were used. The average gap between filaments in the striated samples, as measured by an optical method, was of the order of 0.1 mm. The sample was subdivided as the widths of the filaments were 5 mm including the gaps between the filaments for the 2-filament subdivision and 3 mm, 2 mm, 2 mm and 3 mm from the edge of the tape to the other edge for the 4-filament subdivision.

To investigate the influence of the magnetic substrate on the AC magnetization characteristics, a similar experiment was conducted using YBCO CC sample with non-magnetic Hastelloy substrate. The parameters of this YBCO tape conductor, non-striated, are also given in table 1. Widths of the subdivided tape were 5 mm for the 2-filament subdivision and 2.5 mm for the 4-filament subdivision.

Table 1. Parameters of samples used in the experiment.

| Samples            | HoBCO/Magnetic sub. | YBCO/Non-magnetic sub. |
|--------------------|----------------------|------------------------|
| Width/length       | 10 mm/80 mm          | 10 mm/80 mm            |
| Critical current   | 135 A                | 109 A                  |
| (at 0 T, 77.3 K)    |                      |                        |
| Thickness of Ag layer | 20.0 $\mu$m        | 20.0 $\mu$m            |
| Thickness of SC layer | 1.3 $\mu$m        | 1.0 $\mu$m             |
| Thickness of sub.  | 80.0 $\mu$m          | 100.0 $\mu$m           |

3. Results and discussions

3.1. Critical currents
Critical currents of individual filaments of the subdivided samples for 2-subdivision and 4-subdivision are shown in figure 1. Figure 1 (a) and (b) are for HoBCO and YBCO conductors, respectively. Deterioration in total of the filament critical currents is in small level in the case of the 2-subdivision. In the case of the 4-subdivision, the striation by the chemical etching deteriorated the filament critical currents. This influence of the subdivision on the critical currents was similar in the both cases of the HoBCO and YBCO conductors.

3.2. AC magnetization losses
The measured magnetization losses $Q_m$ [J/cycle/m] per cycle and per unit length of the conductor in the samples for subdivided and non-subdivided HoBCO conductors are plotted against the amplitude of the
AC perpendicular external magnetic field $B_m$ in figure 2 for various frequencies. As seen in figure 2, values of $Q_m$ of the subdivided sample and also of the non-subdivided sample are not dependent on the frequency, which means that the losses are hysteretic and that the filaments were fully electromagnetically decoupled in the experimental condition. The solid lines in figure 2 are calculated based on the Brandt theoretical model for AC magnetization losses in a thin superconductor strip with non-magnetic substrate for a perpendicular external magnetic field [6]. According to this model, magnetization losses $Q_m$, in a strip of width $2a$ and with the critical current $I_c$, are given by:

$$ Q_m = \frac{1}{\mu_0} 4 \pi a^2 B_m^2 \cdot g(x), $$  \hspace{1cm} (1)

where $g(x) = (1/x) [(2/x) \ln \cosh(x) - \tanh(x)]$ and $x = B_m/B_c$; $B_c$ is a characteristic field defined as $B_c = \mu_0 I_c/2 \pi a$. The model was derived for an isolated, single superconducting strip, with a critical current density independent of the magnetic field and uniform within the superconductor strip.

As seen in figure 2, the measured magnetization losses of the non-subdivided HoBCO conductor satisfactorily agree with theoretical predictions given by equation (1), for the magnetic field amplitudes higher than the saturation value, that is $B_c = 6 \text{ mT}$ even though the substrate is magnetic. The remarkable
discrepancies, however, are observed for lower magnetic field amplitudes. We consider that the main reason for such deviations from model is an inhomogeneous distribution of the critical current density within a superconductor layer [7]. As the filaments in the subdivided samples are fully decoupled (at our experimental conditions), the measured losses are supposed to be a sum of loss contributions coming from the individual filaments. The broken and chain lines in figure 2, for subdivided samples, were obtained using equation (1), adopting parameters, i.e. the measured critical current and dimensions, corresponding to each of the filaments of the subdivided samples and taking summation of the calculated losses in the filaments. As seen in figure 2, measured values of $Q_m$ for 2 and 4-subdivisions well agree with the calculated results for $B_m$ higher than 20 mT though the substrate of the sample is magnetic. The values of $Q_m$ in the subdivided samples are compared with those of the non-subdivided sample in figure 3, where $\alpha$ is the ratio of value of $Q_m$ in the subdivided sample to that in the non-subdivided sample. It is clearly seen in figure 3 that the subdivision is effective to reduce the magnetization losses in the whole range of $B_m$ in the experiment.

To compare the loss characteristics of the magnetic substrate samples with those of non-magnetic substrate samples, the magnetization losses in non-subdivided and subdivided YBCO conductor with Hastelloy substrate were measured and graphs similar to those in figure 2 and 3 for HoBCO samples are shown in figures 4 and 5, respectively. Solid, broken and chain lines in figure 4 are calculated based on the same theoretical model used to calculate the lines in figure 2. In the case of non-magnetic substrate CC also, the measured data well agree with the calculated lines for both of non-subdivided and subdivided samples and the subdivision of the superconductor layer is effective to reduce the magnetization losses for $B_m$ higher than saturation value $B_c = 20$ mT. However, as is obvious in figure 5, the subdivision increases the magnetization loss for $B_m$ lower than 6 mT. This contrary effect of the subdivision is commonly observed and a reason for this is considered to be due to the changes in the critical current density distribution within the superconductor layer [7].

It is shown by the above results that the subdivision of the superconductor layer is effective to reduce the magnetization losses due to the perpendicular AC external magnetic field also for the magnetic substrate CCs, as is the same as for the non-magnetic substrate CCs. It is also shown that the reduction of the losses by the subdivision can be estimated by the calculation method using the Brandt equation (1) for
both of the magnetic and non-magnetic substrate CCs.

3.3. Discussions

Figure 6 shows calculated magnetic field distribution $B_s$ in the magnetic substrate of a CC subdivided into 4 filaments subjected to an external perpendicular magnetic field of $B_{ex} = 100$ mT. In this FEM calculation, it is assumed that each of the subdivided superconductor filaments is fully saturated by the shielding current and that the sheet critical current density within the superconductor layer is uniform and 135 A/cm. It is also assumed that the relative permeability of the substrate is 193 which is estimated from the measured data at 77.3 K. Though there are local peaks in $B_s$, the average of $B_s$ is 100 mT nearly equal to the external field.

Figure 6. Magnetic field distribution $B_s$ calculated in the substrate of a magnetic substrate CC subdivided into 4 filaments subjected to external magnetic field $B_{ex}$. The saturated shielding currents flowing in each of the HTS filaments are also shown in the figure.
to the external field $B_{ex}$, as is predicted from the conservation law of the magnetic flux. According to the measured data in [3], AC magnetization loss in the substrate without superconductor layer is $\sim 10^{-3}$ J/m/cycle at $B_m = 100$ mT and much smaller than the AC losses in the subdivided HoBCO CCs. Therefore, the influence of magnetic property of substrate on the AC magnetization loss is negligibly small for the perpendicular external magnetic field.

4. Concluding remarks

AC magnetization losses in subdivided CC with magnetic substrate were experimentally investigated for an AC external magnetic field perpendicular to the wide face of the CC. The experimental results show that the subdivision is also effective for the CC with magnetic substrate and that the level of reduction of the losses by the subdivisions is almost the same as that of non-magnetic substrate CCs.

It is also shown that, if the superconductor filaments are fully decoupled, the magnetization losses in the subdivided CC can be predicted for both of the magnetic and non-magnetic substrate CCs by calculating the magnetization losses in each of the superconductor filaments based on the Brandt equation using parameters of the width and critical current of the filament and taking the summation of the magnetization losses of all of the filaments.

It can be concluded from the above experimental results that the magnetic property of the substrate does not affect the magnetization losses in the subdivided conductor due to the perpendicular external magnetic field. However, it should be pointed out that this conclusion does not hold when number of subdivision is so large that the total of the magnetization losses in the filaments are reduced to the same level of losses of the substrate itself.

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