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RESEARCH ARTICLE

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Experimental investigation on frequency-dependent critical current of HTS tapes

Abstract Based on characteristics of alternating current (AC) critical current of high temperature superconducting (HTS) tapes on the frequency, this paper focuses on AC voltage-current (*U-I*) behaviors of two kinds of high temperature superconducting tapes, by which BSCCO and YBCO carrying different frequency AC currents are tested in liquid nitrogen temperature of 77 K. It is shown that the AC *U-I* characteristic curves of different tapes consist of two parts, that is, the resistive part and the hysteresis part. Additionally, the *n* values of the two parts and the relationship between AC critical current and frequency are obtained through experiments. The experimental results agree with calculated ones well, which is useful for the application of HTS tapes to power technology.

Keywords high temperature superconducting (HTS) tape, alternating current (AC) critical current, *n* value, frequency, AC voltage-current (*U-I*) behavior, four-probe technique

1 Introduction

With development of superconducting power applications, a variety of superconducting electrical equipments, such as high temperature superconducting (HTS) cable [1–3], transformer [4], motor, superconducting magnetic energy storage (SMES) device, and superconducting fault current limiter (FCL) [5,6] have been demonstrated running in several countries [7–10]. The *n* value and critical current are significant parameters for weighing the quality of superconducting materials [11–13]. *n* value describes transferring degree from the superconducting state to normal state. Critical current is an important parameter to measure the carrying current capacity of practical superconducting materials. The study on *n* value and critical current of HTS is able to provide an important reference to production and operation of the HTS power devices [11,12]. In the study of direct current (DC), the critical current of HTS already has a relatively complete theoretical and experimental support. But for alternating current (AC) case, the investigation is still not enough about the AC critical current I_B, that is, the turning point current of crossover from the hysteresis part to the resistive part in voltage-current (*U-I*) curve is defined as AC critical current when HTS tape carrying AC current [14,15]. Furthermore, a lot of researchers mainly focused on theoretical analyses, there are no enough actual measurements on AC *U-I* behaviors. But the superconducting electrical equipments often involve alternating current, so that more detailed experimental study on *U-I* features of HTS tapes carrying alternating current is essential and thus provides important references for the practical application of HTS power.

In this paper, AC *U-I* characteristics for the first generation (1G, BSCCO) and the second generation (2G, YBCO) HTS tapes were tested in liquid nitrogen thermostatic bath by standard four-probe and lock-in-amplifier techniques. According to the experiment result, the relationship between the AC critical current and the frequency has been analyzed by compared theoretical calculation with the experimental result.

2 Analysis models

Traditionally, the critical current of superconductor is defined as the maximum DC current which can transport in the superconductor without resistances. *U-I* characteristic curve of the superconductor could be obtained by the

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four-probe method and then the DC critical current will be acquired. However, the concept of DC critical current cannot accurately describe the critical current of superconductor when it carries AC current. When HTS tape carries AC current, AC critical current is not equal to its DC critical current [8]. Analyses of AC *U-I* characteristic of HTS tapes at different frequencies were reported recently. AC critical current of HTS tapes at different frequencies and the relationship between the AC critical current and the frequency are obtained mainly by simulations, respectively. Generally, analyses on *U-I* behaviors of superconductors include the n value and the critical current. And n is an index parameter and can be found by fitting the *U-I* characteristic curve of the superconductor in accordance with the exponential law with criterion of $0.1\ \mu\text{V/cm} \leqslant E \leqslant 1\ \mu\text{V/cm}$ [7].

$$E = E_{\mathrm{c}}\left(\frac{1}{I_{\mathrm{c}}(B,T)}\right)^{n(B,T)}, \tag{1}$$

where E denotes the electric field per centimeter along longitudinal of superconductor. The voltage is divided by length. $E_{\mathrm{c}} = 1\ \mu\text{V/cm}$ is the criterion for defining the critical current. I_{c} is DC critical current. In general, n is functions of magnetic field B and temperature T. The AC critical current varies with different frequencies which obey

$$I_{\mathrm{B}}(f) = I_{\mathrm{c}}(f_0)\left(\frac{f}{f_0}\right)^{\frac{1}{n}}, \tag{2}$$

where $I_{\mathrm{B}}(f)$ is the AC critical current at different frequencies, $I_{\mathrm{c}}(f_0)$ refers to the DC critical current, f_0 is the frequency when AC critical current $I_{\mathrm{B}}(f_0)$ is equal to the DC critical current I_{c}.

3 Experimental set-ups

Figure 1 shows the schematic arrangement for measuring AC *U-I* characteristic curves of HTS tapes. AC power supply can provide AC current with different frequencies to HTS samples, the range of frequency is 5–1100 Hz. The output current is limited; thus, AC power supply cannot provide enough current to meet experimental requirements. Concerning that, a single-phase transformer was used for enhancing current and dropping voltage in samples. To adjust the current continuously, voltage regulator was employed. Current in samples was measured by a standard resistance that connected with samples in series. Rated voltage and current of the standard resistance are 75 mV and 500 A, respectively. Resistive voltage signal in the sample was measured by a lock-in amplifier (SR830). In our experiments, the lock-in amplifier worked as the external reference mode, the input signal of external reference was provided by a voltage signal on the standard resistance that is amplified by signal amplifier before inputting into the lock-in amplifier in order to meet the required magnitude of reference signal (at least 200 mV). The signal amplifier used in the experiment has a little phase difference between the input signal and the output

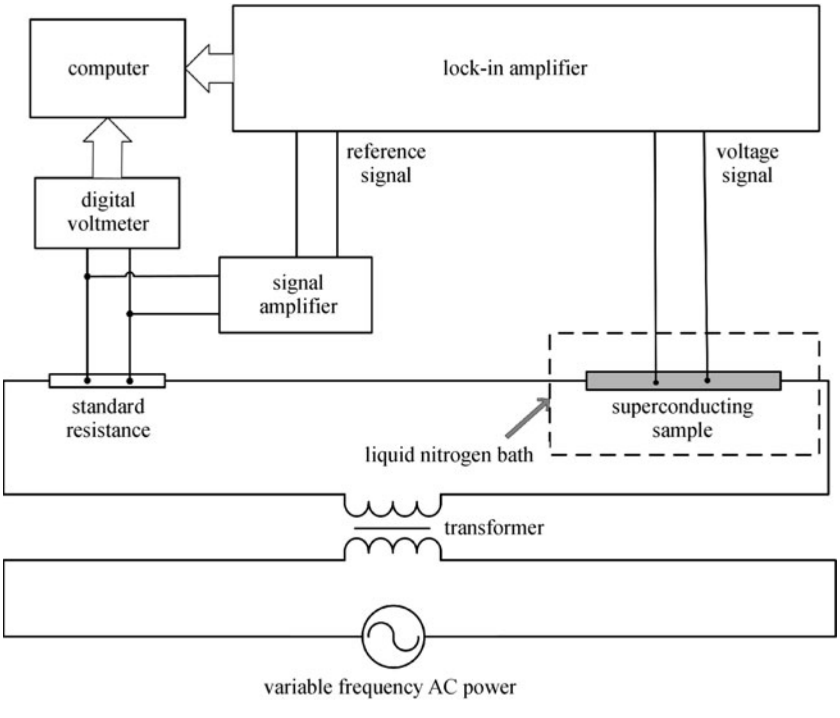

Fig. 1 Schematic arrangements of set-up

signal, as shown in Fig. 2. We use the known relationship between phase difference and frequency to calibrate the resistive voltage signal of the sample, for getting a more accurate measurement results.

The AC *U-I* characteristics of BSCCO and YBCO HTS tapes were measured. BSCCO tape is with cross section of 4.8 mm × 0.3 mm and critical current I_c = 125 A at 77 K and self field. YBCO tape is with cross section of 4 mm × 0.3 mm and critical current I_c = 90 A at 77 K and self field. These experiments were carried out in the liquid nitrogen bath. The range of measurement frequency is 5–210 Hz. The test employed four-probe technique. The entire measurement system was controlled by a computer, and all data were acquired in a LabView environment.

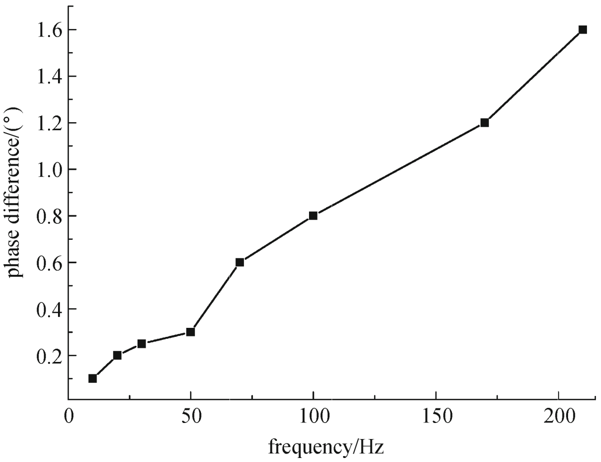

Fig. 2 Dependence of phase difference between the input signal and the output signal of the signal amplifier on frequency

4 Results and discussion

AC *U-I* characteristics of BSCCO and YBCO superconducting tapes were obtained through experiments. Figures 3 and 4 are their AC *U-I* characteristic curves. AC current and voltage are the root mean square value in the two figures. Figure 3 shows the AC voltage and current characteristics at different frequencies of BSCCO. By fitting the data of the hysteresis part according to the power exponent law [11], it could be found that *n* value decreases with increasing frequency, $n = 1.75$ at $f = 10$ Hz and $n = 1.5$ at $f = 210$ Hz, respectively. However, the slope of its resistive part is a constant with the changing frequency, $n = 9.7$. Figure 4 is the AC *U-I* characteristic curves of YBCO coated conductor (YBCO CC) fabricated by American Superconductor Company (AMSC) and is similar with BSCCO, as shown in Fig. 3. In the hysteresis part of the *U-I* characteristic curve, *n* value decreases with the rise of frequency, $n = 1.3$ at $f = 5$ Hz and $n = 1.2$ at $f = 170$ Hz. The slope of the resistive part does not vary with the frequency, $n = 21$. Above experimental results are consistent with the simulating results of Ref. [8].

As it has been already mentioned in the previous paper [8], the AC critical current corresponds to the crossover point current in hysteresis and resistive parts, respectively. Trends of the AC critical current are displayed in Figs. 3 and 4. Figure 5 illustrates the relationship between AC critical current and the varying frequency. The AC current in Fig. 5 is the amplitude of applied AC current. It can be clearly seen that the AC critical currents of BSCCO and YBCO increase with increasing frequency. Because minimum frequency of AC power is 5 Hz, the AC critical current could not be measured at frequency below 5 Hz. However, the tendency of the figures shows that if the

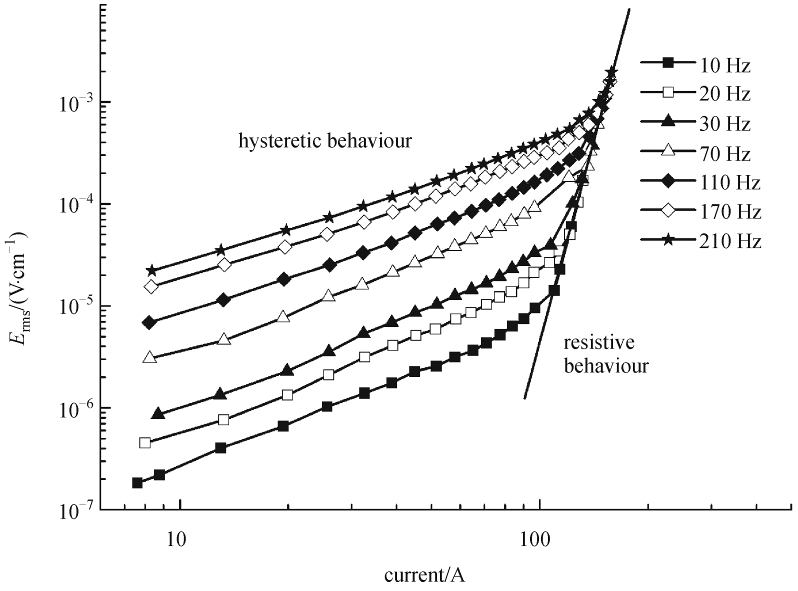

Fig. 3 AC *U-I* characteristic curves at different frequencies for BSCCO tapes

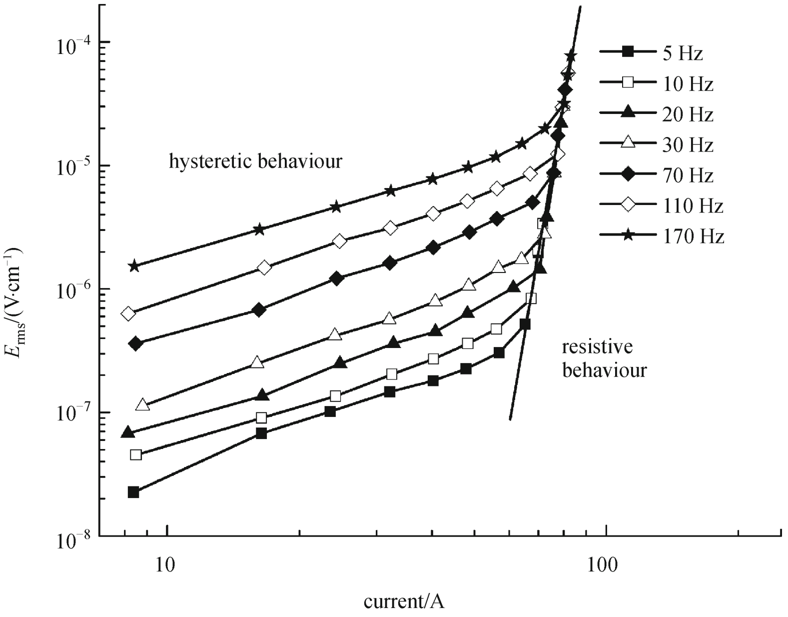

Fig. 4 AC *U-I* characteristic curves at different frequencies for YBCO CC

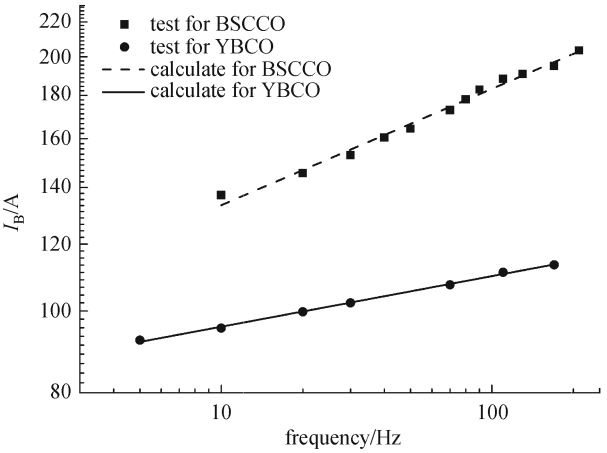

Fig. 5 Frequency-dependent AC critical currents of BSCCO with DC critical current I_c = 125 A and YBCO CC with I_c = 90 A

frequency is low enough, the AC critical current of the tapes might have been less than or equal to the DC critical current. With fitting the experimental data in Figs. 3 and 4, respectively, the results are shown in Fig. 5 that AC critical currents of BSCCO and YBCO change with frequency, where the solid line and dotted line are the calculated values according to Eq. (2), scatter denotes data of experimental test. By fitting the experimental data, we obtain n = 7.29, f_0 = 1.45 Hz and n = 17.9, f_0 = 3 Hz, respectively for the BSCCO and YBCO CC. It shows that the experimental data are qualitatively in agreement with the calculated ones due to the limited frequency range used in the experiments. Above all, the experiments and analysis were achieved at self field, but characteristics of AC critical current for HTS tapes within an external magnetic field require further research.

The AC critical current, $I_B(f)$, increases with the rise of the frequency. The mechanisms of this phenomenon are not surely clear up to now, but the possible reasons suggested are as follows:

1) It could be the result of the thermally activated creep of vortices, which are formed in a system with refined junctions caused by plastic deformations flux creep in superconductor [16].

2) The flux diffusing into the sample should take a finite time, and the growth rate of the current increases with increasing frequency. At high frequency $f > f_0$, the flux diffusion is slower than the growth of current. The magnetic flux cannot penetrate the sample as deep as at low frequency or DC cases with increase of frequency. There possibly exists a larger “flux free” area in the central part of the sample at high frequency. Consequently, a generously proportioned current is needed for full penetration of the flux at high frequency, which results in increasing the AC critical current at high frequency [8].

3) The current density distributions in superconductor and the skin effects also could be the reason for this result. The highest current density value in HTS tapes is obtained in the outer filaments [17], in which current distribution in the cross section of tapes is not uniform, that is, the closer the conductor surface, the larger the current density. Therefore, the AC current carrying capability increases with the increasing frequency.

5 Conclusions

Experimental investigation on frequency-dependent critical current of HTS tapes was accomplished at 77 K and self field. Frequency-dependent critical current could be obtained from the HTS AC voltage-current characteristic curve. It is shown that the n value of the hysteresis part decreases with increasing frequency, while the slope of the resistive part does not vary with changing frequency. AC critical currents of two kinds of HTS tapes increase with increasing frequency, and AC critical current $I_B(f)$ is approximately proportional to $f^{1/n}$. And the experimental results qualitatively agree with the theoretical ones. The theoretical analysis and experimental studies in background of AC and DC magnetic fields need to perform in next step.

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References

1. Mukoyama S, Maruyama S, Yagi M, Yagi Y, Ishii N, Sato O, Amemiya M, Kimura H, Kimura A. Development of 500 m HTS power cable in super-ACE project. Cryogenics, 2005, 45(1): 11–15
2. Xin Y, Hou B, Bi Y F, Xi H X, Zhang Y, Ren A, Yang X C, Han Z H, Wu S T, Ding H K. Introduction of China's first live grid installed HTS power cable system. IEEE Transactions on Applied Superconductivity, 2005, 15(2): 1814–1817
3. Furuse M, Fuchino S, Higuchi N. Investigation of structure of superconducting power transmission cables with LN2 counter-flow cooling. Physica C: Superconductivity, 2003, 386: 474–479
4. Schlosser R, Schmidt H, Leghissa M, Meinert M. Development of high-temperature superconducting transformers for railway applications. IEEE Transactions on Applied Superconductivity, 2003, 13 (2): 2325–2330
5. Hatta H, Nitta T, Oide T, Chiba M, Shirai Y, Mochida A. Experimental study on characteristics of superconducting fault current limiters connected in series. Superconductor Science and Technology, 2004, 17(5): S276–S280
6. Luongo C A, Baldwin T, Ribeiro P, Weber C M. A 100 MJ SMES demonstration at FSU-CAPS. IEEE Transactions on Applied Superconductivity, 2003, 13(2): 1800–1805
7. Wang Y S, Guan X J, Zhang H Y, Liu H W. Progress in inhomogeneity of critical current and index n value measurements on HTS tapes using contact-free method. Science China Technological Sciences, 2010, 53(8): 2239–2246
8. Thakur K P, Raj A, Brandt E H, Kvitkovic J, Pamidi S V. Frequency-dependent critical current and transport ac loss of superconductor strip and Roebel cable. Superconductor Science and Technology, 2011, 24(6): 065024
9. Tao B W, Xiong J, Liu X Z, Li Y R. Progress in research of coated conductors. Materials China, 2009, 28(4): 16–22 (in Chinese)
10. Cheng S J, Tang Y J. High temperature SMES for improving power system stabilities. Science in China Series E: Technological Sciences, 2007, 50(4): 402–412
11. Wang Y S. Superconducting Power Technology. Beijing: Science Press, 2011 (in Chinese)
12. Lin L Z, Zhang J L, Li C Y, Xia P C, Yang Q S. Superconductivity Application. Beijing: Beijing University of Technology Press, 1998 (in Chinese)
13. Wang H L, Wang J R. Application of Low Temperature Superconducting Technology. Beijing: National Defense Industry Press, 2008 (in Chinese)
14. Kudymow A, Schacherer C, Noe M, Goldacker W. Experimental investigation of parallel connected YBCO coated conductors for resistive fault current limiters. IEEE Transactions on Applied Superconductivity, 2009, 19(3): 1806–1809
15. Saleh A M, Abu-Samreh M, Al-Awaysa G M, Kitaneh R M-L. Extraction of critical current density and flux creep exponent in the magnetic superconductor Ru-1212 using the ac magnetic susceptibility measurements. Journal of Superconductivity and Novel Magnetism, 2008, 21(4): 229–235
16. Qu T M, Luo X M, Chen D X, Han Z. Frequency dependence of ac susceptibility of monofilament Bi-2223/Ag superconducting tapes. Physica C: Superconductivity, 2004, 412–414(2): 1154–1157
17. Stavrev S, Dutoit B, Nibbio N, Le Lay L. Eddy current self-field loss in Bi-2223 tapes with a.c. transport current. Physica C: Superconductivity, 1998, 307(1–2): 105–116