Quench characteristics of high-T_C superconducting tape for alternating over-current using DFT

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The quench characteristics of high-T_C superconducting (HTSC) tape for alternating over-current were investigated and its quench developments using discrete fourier transform (DFT) were analyzed. Generally, the voltage-current characteristics of HTSC tape for the alternating over-current are complicated because the quench and the recovery between the superconducting state and the normal state are repeated. In this paper, the numerical formulation for HTSC tape's resistance was obtained by applying DFT for the measured data. By applying its numerical formulation into circuit equation, the quench developments of HTSC tape dependent on alternating over-current could be estimated and well agreed with experimental results.

INTRODUCTION

With the efforts to overcome mechanical weakness and critical current of high-T_C superconducting (HTSC) tape for power application, its critical and mechanical characteristics have been improved [1]. However, quench characteristics of HTSC tape, which occurs when the transporting current exceeds its critical current, are complicated because of the repeated transition between the quench to the normal state and the recovery to the superconducting state [2]. Especially, the analysis for the quench development of HTSC tape is needed to protect it from thermal runaway, and to keep safety operation in the power machine using HTSC tape. In this paper, we investigated the resistance development of HTSC tape after alternating over-currents were applied into it and induced the numerical expression by applying discrete fourier transform (DFT) for the measured voltages and currents. It was confirmed that the resistance development of HTSC tape dependent on the amplitude of alternating over-current could be estimated by introducing its expression into the circuit equation and the similar results to the experimental ones could be obtained.

OVER-CURRENT CHARACTERISTIC TEST AND NUMERICAL FORMULATION

HTSC tape used in this experiment, which was fabricated by power in tube (PIT), had the critical current of 57 A and the critical temperature of 106 K. Its size was 3.81 mm wide and 0.193 mm in thickness. The length of HTSC tape prepared for the over-current test was 110 cm. Two voltage taps were attached with 100 cm distance on the surface of HTSC tape after twisting to minimize the area between the voltage taps and the surface of the tape. Voltage and current signals, which were measured with the voltage and current probes, were obtained by data acquisition system with multi-channels. The over-current whose amplitude was regulated by a power supply with a transformer was applied into HTSC tape during 6 periods. To investigate the resistance development of HTSC tape for alternating over-current, the voltages between two voltage taps and the transport currents were measured after over-currents from 100 A_{peak} to 600 A_{peak} with difference of 50 A_{peak} were applied into HTSC tape. The resistance component of HTSC tape with the fundamental power source frequency could be obtained from the impedance (equation (2)), which was equal to the ratio of the voltage data for the current data (as expressed in equation (1)) extracted using discrete fourier transform (DFT) for the measured voltage and current signal data.

$$X(jkf)=\sum_{n=1}^{N} x(e^{-knfT})=[\,x(T) \quad x(2T) \quad \cdots \quad x(NT)\,]\cdot\begin{bmatrix} e^{-jkfT} \\ e^{-2jkfT} \\ \vdots \\ e^{-jknfT} \end{bmatrix} \tag{1}$$

$$Z=V(jkf)/I(jkf) \tag{2}$$

Where T, N and f represent sampling length, sampling number per period and fundamental frequency, respectively.

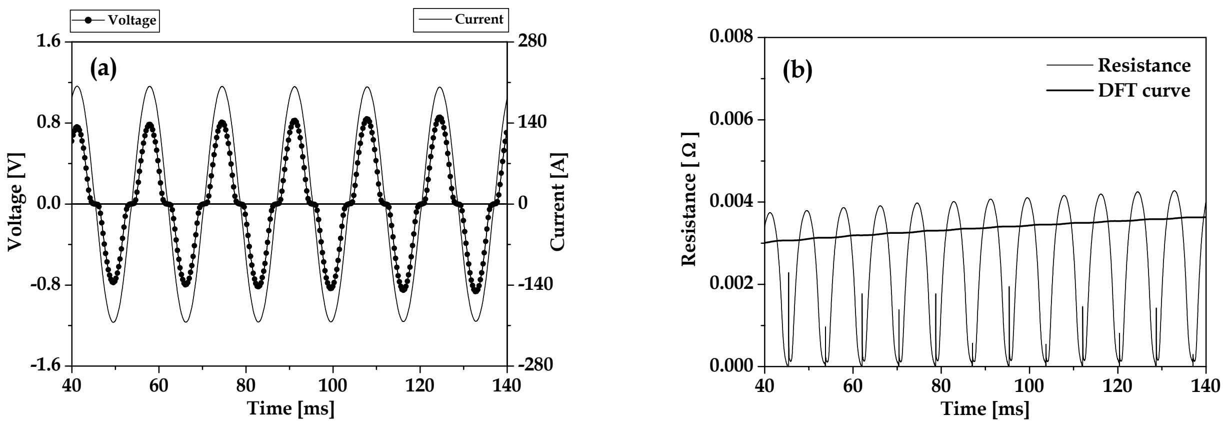

Figure 1 Quench characteristics in case that source current with 204 A_{peak} was applied into HTSC tape (a) Waveforms of alternating over-current and voltage across HTSC tape (b) Resistance and DFT curve of HTSC tape

Figure 1(a) shows the source current waveform of 204 A_{peak} and the voltage waveform across HTSC tape. The resistance waveform, which can be calculated by dividing the voltage waveform of HTSC tape with the source current waveform as seen in Figure 1(a), was shown in Figure 1(b). As seen in Figure 1(b), the HTSC tape at the point that the sinusoidal source current approached to zero recovered to superconducting state, namely, its resistance approached to zero value temporarily. DFT curve for the resistance of HTSC tape obtained by applying the equation (1) for the measured current and voltage waveforms was also added into Figure 1(b). The DFT curve for the resistance of HTSC tape smoothly increased along with its peak resistance value. Another DFT curve for the resistance of HTSC tape in case that the source current of 306 A_{peak} was applied was shown in Figure 2(b), which was obtained from the HTSC tape's voltage and the source current waveforms (Figure 2(a)). As seen in Figure 2(b), DFT curve for the resistance of HTSC tape, which increased as the peak value of HTSC tape's resistance increased, increased with larger value than in case of the source current of 204 A_{peak}.

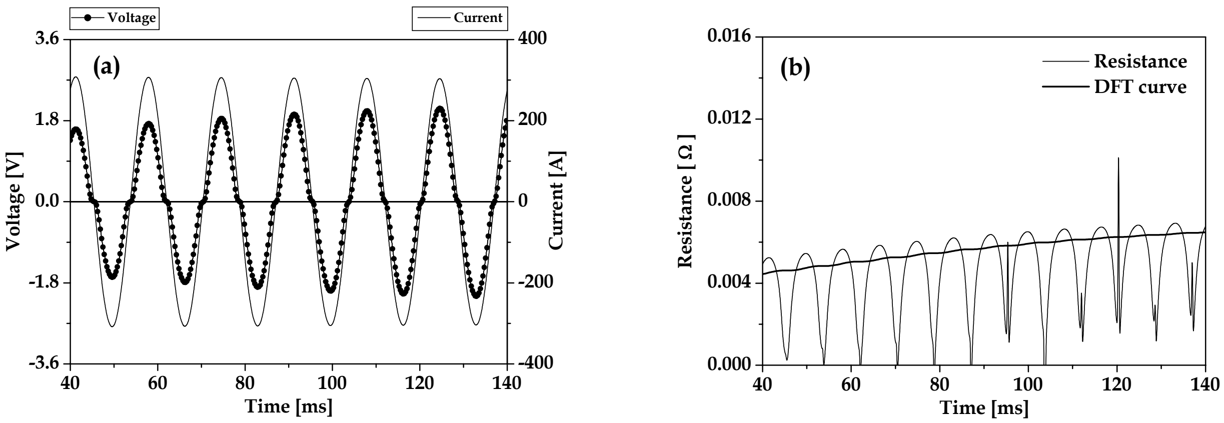

Figure 2 Quench characteristics in case that source current with 306 A_{peak} was applied into HTSC tape (a) Waveforms of alternating over-current and voltage across HTSC tape (b) Resistance and DFT curve of HTSC tape

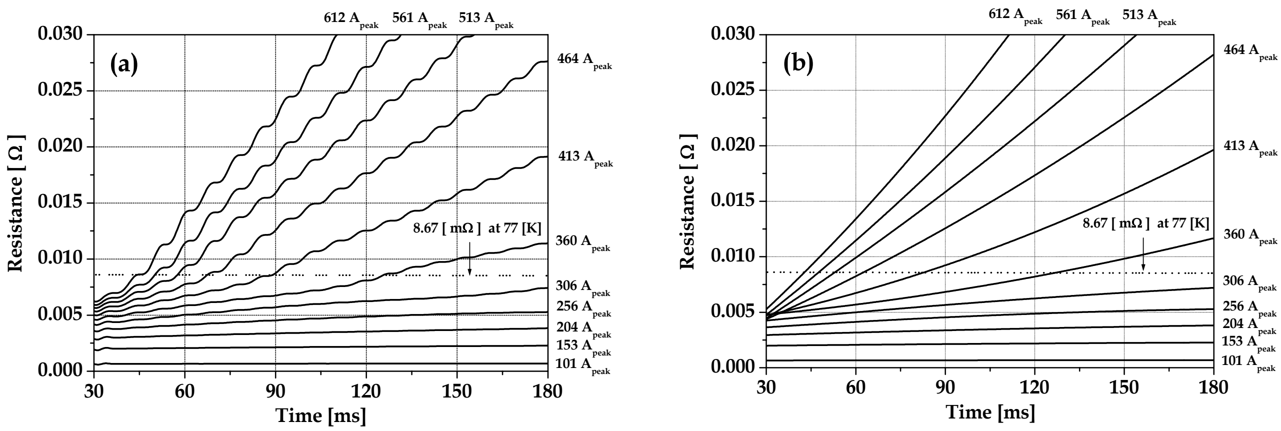

Figure 3 DFT curves for HTSC tape's resistances dependent on the alternating over-current from 101 A_{peak} to 612 A_{peak} (a) DFT curves for HTSC tape's resistances obtained by using equation (1) (b) DFT curves for HTSC tape's resistances obtained by applying the least square method for DFT curves of Figure 3(a)

DFT curves for HTSC tape's resistances dependent on the alternating over-current from 101 A_{peak} to 612 A_{peak}, which could be extracted as explained above, were shown in Figure 3(a). Figure 3(b) shows the DFT curves for HTSC tape's resistances obtained by applying the least square method for DFT curves of Figure 3(a). Each DFT curve in Figure 3(b) was fitted to a quadratic function of time as expressed in equation (3).

$$R(t,I)=C_1(I)\cdot t^2+C_2(I)\cdot t+C_3(I) \tag{3}$$

where C_1, C_2 and C_3 are supposed to be presented as the function of over-current (I). The values of C_1, C_2 and C_3 for different over-currents could be obtained by approximating DFT curves of Fig. 3(b) to polynomial equations for over-current using least square method. By applying the equation (2) for the circuit equation including power source and source resistance, we could estimate the quench development of HTSC tape dependent on alternating over-current. Figure 4(a) and Figure 4(b) show the simulated waveforms for the application of alternating over-currents with 204 A_{peak} and 306 A_{peak} to HTSC tape, whose calculation conditions correspond to Figure 1(b) and Figure 2(b). As compared Figure 4(a) and Figure 4(b) with Figure 1(b) and Figure 2(b), we confirmed that the numerical expression for HTSC tape's resistance derived from the experiments agreed well with the measured results.

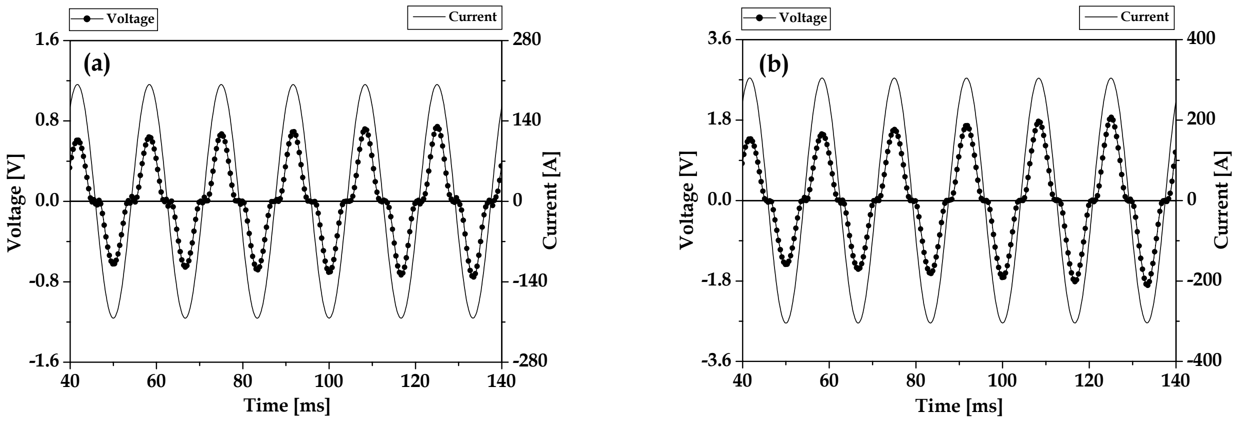

Figure 4 Simulated waveforms of alternating over-current, voltage across HTSC tape (a) In case that source current with 204 A_{peak} was applied into HTSC tape (b) In case that source current with 306 A_{peak} was applied into HTSC tape

CONCLUSIONS

In this paper, we investigated the resistance development of HTSC tape after alternating over-currents were applied into it and induced the numerical expression of it using discrete fourier transform (DFT) from the measured voltages and currents. It was confirmed that the resistance development of HTSC tape dependent on the amplitude of the over-current could be estimated by applying its expression into the circuit equation and the similar results for the resistance development to the experimental ones could be obtained. We will research the current distribution between the superconducting part and the Ag sheath of HTSC tape for alternating over-current application.

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