Current Instability of High Temperature Superconducting Tapes in the AC Modes

V Romanovskii [a], *IEEE Member*, K Watanabe [b] and S Awaji [b]

[a] NBIKS-Centre, National Research Centre "Kurchatov Institute",
Moscow, 123182, Russia

[b] High Field Laboratory for Superconducting Materials, Institute for Materials
Research, Tohoku University, Sendai, 980-8577, Japan

E-mail: vromanovskii@netscape.net

Abstract. The basic physical reasons rooted in the current instability phenomenon of AC regimes are discussed. To explain their stable formation, the conduction-cooled high-temperature superconductors (HTS) are investigated studying mutually dependent thermal and electrodynamics states of a tape. It is proved that there exist characteristic times defining time windows of stable development of overloaded AC regimes. They lead to the states for which the limiting peak values of charged current and induced electric field before instability onset much more than the corresponding critical values of a superconductor. Moreover, the limiting stable peak values of the temperature, electric field and current are higher than the corresponding quench ones calculated at DC modes. It is shown that the stability boundary of overloaded AC modes slowly depends on the current frequency. As a result, the high-T_c superconducting magnets may stably operate under very high AC losses even at the conduction-cooled conditions. The obtained results should be taken into consideration when the range of stable losses is defined in HTS during AC regimes.

Introduction

The boundary of the current instability onset is an important factor, which determines the limitation in the possible application of superconductors. To design a high-temperature superconducting magnet with high operational properties, it is possible to use the regimes when a charged current is larger than the critical current of a superconductor. For example, the HTS operating regimes are stable in the overcurrent pulses [1]-[5]. At the same time, the mechanisms, which lead to the existence of the stable overloaded AC regimes, are not discussed. The presented below investigation allowed to formulate the thermo-electrodynamics mechanisms underlying the stable formation of overloaded AC regimes in HTS tapes.

2. Alternating current model of HTS tapes

Let us investigate the formation of AC regimes in a cooled superconducting tape ($-a < x < a$, $-\infty < y < \infty$, $-b < z < b$, $b >> a$) placed in a fully penetrated DC external magnetic field B. Assume that a superconducting core is uniformly distributed over a cross section of a tape with the volume fraction coefficient η; the sinusoidal current I having peak value I_m is charged in the y-direction and its self-field is greatly less than the external magnetic field. To make the analysis without excessive

computations, let us accept that the temperature and electric field are uniform over the cross section of a tape for which the superconductor's voltage-current characteristic is described by a power low with the linear temperature dependence of the critical current density J_c. In accordance with these assumptions, the thermal and electric states of a superconducting tape depend on the currents flowing in the superconducting core J_s and the normal conducting sheath J_n. Therefore, the following equations

$$C(T)dT / dt = -hp(T - T_0) / S + E(t)I(t) / S, \quad T(0) = T_0 \tag{1}$$

$$E(t) = E_c \left[J_s(t) / J_c(T, B) \right]^n = J_n(t)\rho_n(T, B), \quad E(0) = 0, J_c = J_{c0}(T_{cB} - T) / (T_{cB} - T_0) \tag{2}$$

$$I(t) = \eta J_s(t)S + (1-\eta)J_n(t)S, \quad I(t) = I_m \sin(2\pi ft) \tag{3}$$

may be used to describe the dynamics of the temperature and electric field in zero-dimensional approximation according to the continuous medium model. Here, C is the specific heat capacity of tape, h is the heat transfer coefficient, S is the cross section of tape, p is the cooled perimeter, E_c is the voltage criterion used in the J_c definition, n is the power exponent of the E - J curve, J_{c0} and T_{cB} are the critical parameters of a superconductor at the given external magnetic field, f is the current frequency.
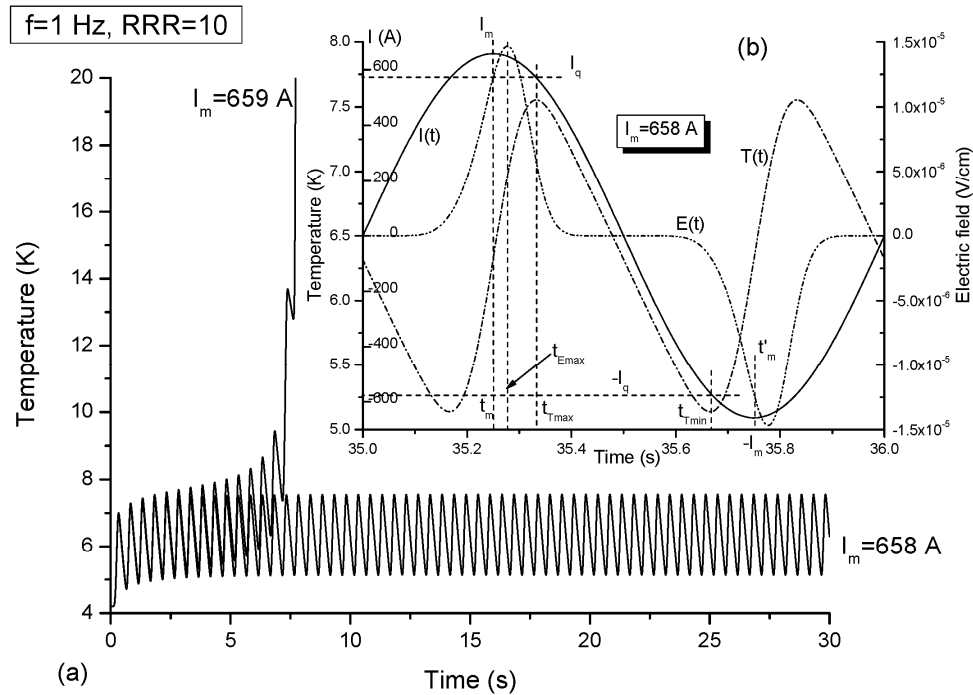
As an example, we take the tape to be Ag/Bi2212 during the calculations. The sheath residual resistivity ratio RRR=$\rho_n(273\ K)/\rho_n(4.2\ K)$ was varied assuming that $\rho_n(273\ K)$=1.48×10^{-6} Ω·cm according to [6]. The sheath resistivity as a function of temperature and magnetic field was approached by the relations proposed in [6, 7]. The following parameters $a = 0.019$ cm, $b = 0.245$ cm, $S/p = a$, $\eta = 0.2$, $n = 10$, $E_c = 10^{-6}$ V/cm, $J_{c0} = 1.5×10^5$ A/cm^2, $T_{cB} = 26.1$ K were set. The simulation was made at operating temperature T_0=4.2 K assuming that the external magnetic field is equal to B=10 T and the heat removal conditions on the surfaces of the tape take place at h=10^{-3} W/(cm^{2}K). The values of the peak current and frequency were varied. The heat capacities of the superconductor C_s and the sheath C_n are taken into account to calculate the heat capacity of the tape in the form $C(T)=\eta C_s(T)+(1-\eta)C_n(T)$ in compliance with the additive law. The temperature dependence of the heat capacity of a superconductor was given as in [8]. The heat capacity of silver was calculated in accordance with [6].
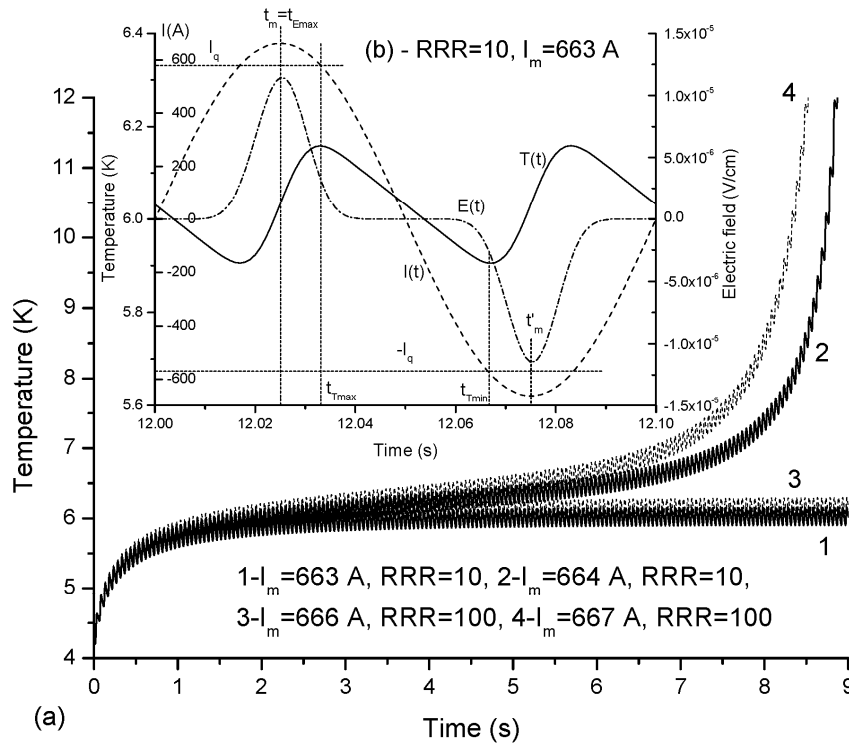
3. Results and discussion

Figures 1 and 2 prove the existence of the stability boundary of overloaded AC regimes. Note that the critical current of the tape equals 566 A in the case under consideration. Besides, the calculations, which were made according to the current instability theory discussed in [9], depict that the DC-quench values of the electric field, current and temperature equal $E_q = 2.9×10^{-6}$ V/cm, $I_q = 573$ A, $T_q = 5.9$ K at RRR=10, respectively. The presented results show the following features of the AC formation regimes.

There are the stable and unstable regimes, which are similar to regimes observed in superconductor near the DC stability boundary. Thereby, the limiting peak current exists, which defines the stability boundary of the overloaded AC regimes in HTS tapes. At the same time, the limiting stable peak values of charged current and induced electric field are greater than the critical ones. Moreover, these values also exceed the corresponding DC-quench values. In particular, the stable peak value of the electric field is over 10 times greater than a priori chosen critical electric field in the both operating regimes depicted in figures 1b and 2b. As a result, this feature leads to the high level of the stable AC losses. As the calculations show, the peak value of the heat generation power ($G=EJ$) exceed 0.4 W/cm^3 during stable overloaded state at f=10 Hz and RRR=100. It is a very important result for a practical superconductivity application because these intensive losses do not destroy the superconducting properties of HTS tapes.

Figures 1b and 2b allow to understand the features leading to such overloaded AC regimes. They demonstrate the characteristic stages of their evolution, which, first of all, depend on frequency.

Figure 1. Stable and unstable temperature evolution (a) and typical stable stages (b) of the overloaded AC regime at $f = 1$ Hz at high resistivity of a silver sheath for Ag/Bi2212.

Figure 2. Stable and unstable temperature evolution (a) and typical stable stages (b) of the overloaded AC regime at $f = 10$ Hz and different resistivity of a silver sheath for Ag/Bi2212.

They can consist of four or three time windows in the first half of charging cycle. First of all, let us discuss the formation peculiarities of the regime that take place at f=1 Hz (figure 1b). During this current load, the temperature still increases although the charged current decreases in the initial stage that starts after $t = t_m$. This stage is in the time interval $t_m < t < t_{Emax}$ where t_{Emax} is the time when the electric field has a maximum. As calculations show, the heat generation in a tape ($G=EJ$) exceeds the heat removal ($W=h[T-T_0]/a$) in this time interval. However, the heat removal has maximum at $t = t_{Emax}$. Therefore, the induced electric field starts to decrease at $t > t_{Emax}$. This is second stage when decreasing current passes into the corresponding value of the DC-quench current ($I(t) < I_q$). This stage exists in the time interval $t_{Emax} < t < t_{Tmax}$ where t_{Tmax} is the time when the temperature of a tape has a maximum. Therefore, the temperature of the superconductor continues to rise in this stage. The joint reduction of the electric field and current leads to the third stage at $t > t_{Tmax}$. It is characterized by decreasing temperature. Thereby, the stable decrease of the current, electric field and temperature take place at $t > t_{Tmax}$. The end of this stage is determined by t_{Tmin} after which the heat generation starts to exceed the heat removal, as the calculations show. Therefore, it is the fourth stage when the temperature of a tape starts to increase. In the end of this stage, the electric field and the current equal the corresponding peak values $-E_m$ and $-I_m$, respectively. The next mode of the AC regime evolution repeats the above-discussed stages and the stable cycle development goes on.

Figure 2b demonstrates that the first stage existing after I_m may be absent when the frequency increases. As calculations depict for the tapes under considerations, the current and the electric field decrease simultaneously in the first stage when the current frequency is more than 3 Hz. But the remaining stages repeat the above-discussed ones. As a whole, the calculations indicate that:
– the higher the current frequency or the lower the critical current density of a superconductor, the lower the first time window;
–the higher the sheath resistivity, the lower the first time window;
– the higher the heat capacity, the lower the first time window.

All of these peculiarities lead to the fact that the limiting instability currents of high-T_c superconducting tapes depend weakly on the current frequency during AC regimes.

4. Conclusion
The mechanisms underlying the existence of stable overloaded AC regimes in HTS tapes are investigated. It is shown that formation of them has the stages, which are defined by characteristic time windows depending on frequency, properties of a Bi2212 superconductor and a silver sheath. This feature defines the existence of the limiting value of a peak current of stable overloaded AC regimes. It is higher not only the critical current of a superconductor but also the corresponding quench current defining the current stability boundary in the DC regimes. Besides, stable peak values of the electric field and temperature are also higher than the related DC-quench values. These results demonstrate that the application of overloaded AC regimes would be very successful for many superconducting electro- power devices.

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