Characterization of the quenching process and the protection of an ac high temperature superconductor coil

Li X. H., Wang Y. S., and Xiao L. Y.

Applied Superconductivity Laboratory, Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing 100080, China

Experimental characterization and numerical simulation of the quenching process in a test high temperature superconductor (HTS) coil were made. The results show that heat accumulation is the key point that causes quenching. The effective critical current of the coil decreases with the temperature increasing. This enhances both the ac loss and the current sharing effect. Consequently, the first step of quenching will occur within a second. Detecting this and making a quick response are important for protecting the ac coil. Based on our results, some criteria were concluded for detecting this first step of quenching.

INTRODUCTION

Devices based on the HTS are nowadays more and more widely utilized in a variety of areas, especially in electrical power applications, such as transformers, power cables, motors and SFCLs [1]. Many of these applications consist of a HTS coil. Therefore, the stability of the HTS coil working at high ac currents becomes more and more important. The modeling and simulating work done recently based on a test HTS coil confirms the important role of heat accumulation in the quench processes [2]. The heat sources can be very different, a typical one is the Joule heat generated by the point at which the working current $I_w > I_c$. Here I_c is the critical current of the superconductor at the point. Other sources such as vortex motion and mechanical disturbance must be also considered in the evaluation of the coil stability. However, in dc cases, the heat accumulation normally starts only after $I_w > I_c$. The heat generated in the “hot” point can be transferred to the environment, and the point is then cooled down. A thermal runaway quench only occurs after the cooling rate is exceeded by the heating rate. In ac cases, the competition of cooling and heating is in principle the same except that the coil is heated up continuously by the ac loss as long as I_w is applied. Since the ac loss is proportional to I^{α}, where α is decided by the frequency [3], with increasing of I_w, an “unexpected” quench can occur without any obvious disturbance. This is very harmful for the coils used in power applications and magnets. To evaluate the effects of ac losses on the quench process, simulation based on the model of the test coil [2] and experimental investigation on the same coil were made. Combining the simulation and experiment results, some criteria of quench detection can be concluded for the quench protection system. All ac currents and voltages used here are RMS values.

SIMULATION AND EXPERIMENT

The simulation model based on the test coil was developed as described in a previous work [2]. A working current slightly beyond the maximum safe working current [4] was applied to make sure that the coil would quench after working for several minutes. As shown in Fig.1, the temperature of the hottest point in the coil reaches the zero-field T_c at about 400 second. However, as shown in Fig.2, the resistance and the voltage across the coil started to rise much earlier. Therefore, it is rather difficult to define when the quench starts. Actually, according to the simulation result, we argue there are two steps of quench in the coil. The first step occurs at part of the coil becomes non-superconductive, either due to heat accumulation or an external disturbance. This step is reversible as the part can be cooled down and become superconductive again. However, the second step is non-reversible, since it occurs after the heating rate exceeds the cooling rate. To protect a coil from quenching, it is necessary to cut off I_w before the second step. Hence, detecting of the first step of quenching is very important.

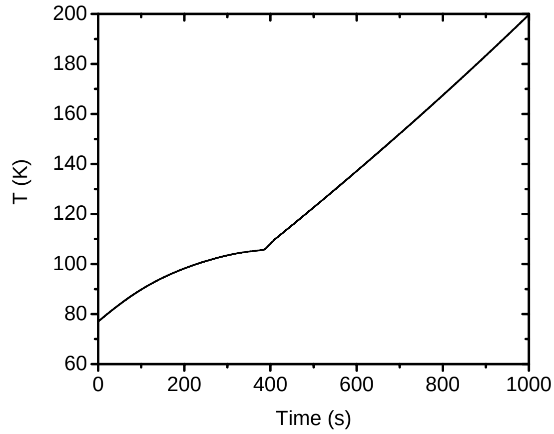

Figure 1 The simulated temperature T of the hottest point in the test coil quenching by over-current

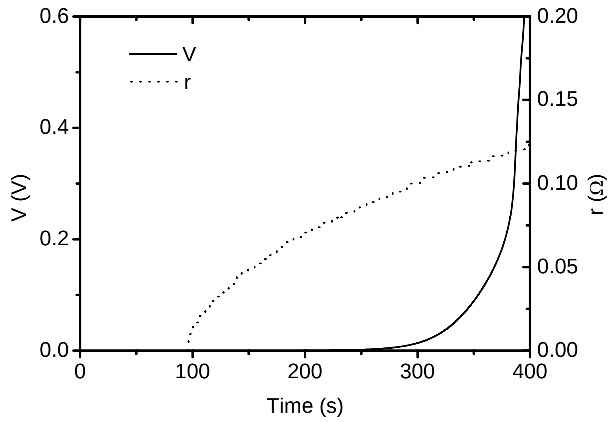

Figure 2 The simulated voltage V and resistance r across the coil during the quench process

The heating rate of a certain section in the coil is not a constant. The critical current I_c at a certain section is a function of the magnetic field B and the temperature T at that section. It will drop to nearly zero at a temperature close to T_c. When $I_c < I_w$, current sharing will occur and causes Joule heat. Moreover, as I_c dropping, the ac loss is also increasing. This has to be added to the heat accumulation, too. Therefore, finding out when the first step of quenching occurs by simulation demands a lot of calculation.

On the other hand, to investigate the quench process experimentally is also difficult. A simple test circuit was setup in our work. It consisted of the coil, which was soaked in liquid N_2, a programmable ac power source and an ac voltage meter measuring the voltage across the coil. Variant I_w was applied to the coil by the power source. As shown in Fig. 3, the voltage across the coil V increases with I_w, nearly linearly. No clear quenching effect of V as shown in Fig. 2 can be detected, even if I_w already exceeds the dc I_c of the coil, which is 2.8 A. Besides this, as shown in Fig. 3, the V/I value is also much higher than the commonly expected resistance of the coil. This is the effect of the inductance. As shown in Fig. 4, a series of total resistance r can be measured by changing frequencies f of I_w. The inductance of the coil can then be calculated from the relation of r and f. However, the calculated inductance is not the same for different frequencies. This indicates the voltage across the coil was generated from more complicated sources besides the inductance and the dc resistance of the coil. As shown in Fig. 2, the dc resistance of the coil is about 0.12 Ω, if it is in the normal state. One of these extra voltages across the coil comes from the ac loss. As the current and frequency increase, the voltage generated by the ac loss becomes more and more significant. A lock-in technique can be used to divide this voltage and the effect of the inductance, because the ac loss voltage has the same phase of I_w, while the effect of the inductance is 90^o later. But it is not possible to distinguish the ac loss voltage and voltage rise of quenching. Although it was thought that the quenching process will happen in a sudden, as shown in Fig. 2, the voltage across the coil V increases slowly and mach later after the first step of the quenching. On the other hand, as shown in the simulation, the increase of V caused by quenching, which is about 0.5 V, is also not very obvious compared to the effect of the inductance and the ac loss voltage. Actually, in our experiment, the sharp increasing of V due to quenching was not clearly detected at all.

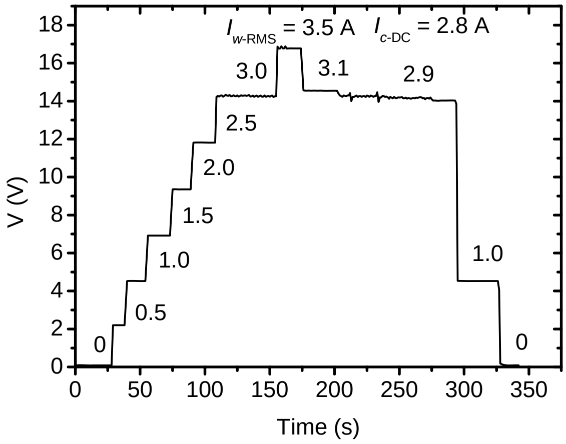

Figure 3 The experimental voltage V across the test coil while applying variant ac currents

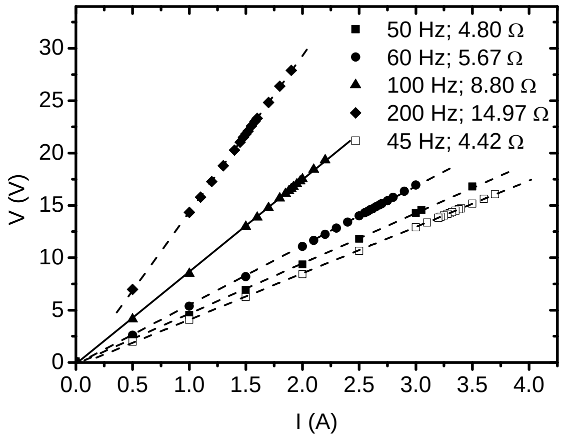

Figure 4 The I-V correlation of the coil at different frequency f of the working current.

By analyzing the experimental data more carefully, we found that, at a certain I_w, the voltage across the coil V is not as stable as at other I_ws. In Fig. 5 this phenomenon is illustrated. The voltage oscillation is not very significant, but it is beyond the error level of the ac power source. Tentatively, we take this as an evidence of the ac critical current I_c' of the coil. At I_c', the coil starts to quench. The quenching process can be described as below: At first, because of heat accumulation or disturbance, some section of the coil reaches a temperature where $I_c = I_w$. Current sharing then starts at this section, which leads to an increase of the resistance and voltage. After this, the section is heated up to a higher temperature. With higher temperature, the cooling rate of the section can be a little faster, too. If the cooling rate exceeds the heating rate, the section can be cooled down again. Finally, at the cooled section, the heat will accumulate again, and starts another cycle of the oscillation. As shown in the figure, the period of the oscillation suggests that this reversible first step of quenching can occur within one second.

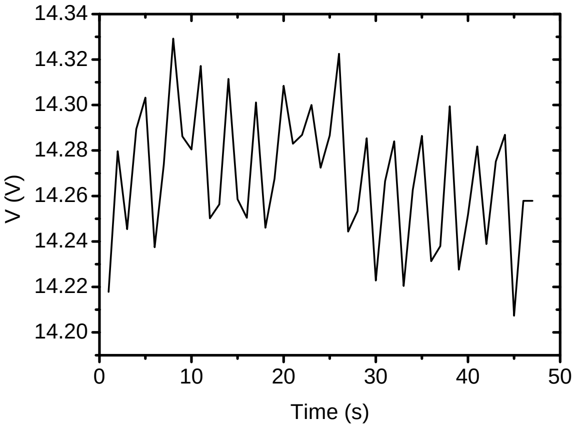

Figure 5 A typical oscillation of the voltage across the coil at the ac critical current.

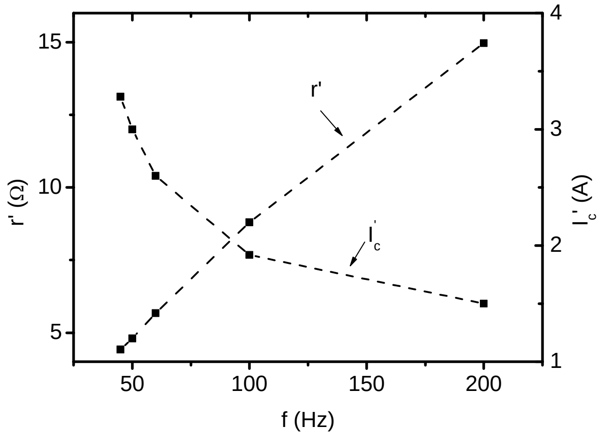

Figure 6 The frequency effect on the impedance r and the ac critical current I_c'

According to the phenomenon described above, the ac critical current I_c' of the test coil was measured at different frequencies. The result is shown in Fig. 6, along with the total impedance r' calculated by linear fitting of the I-V correlation curves shown in Fig. 4. From this figure, it is clear that, with increasing frequency, I_c' nonlinearly decreases, while r' increases nearly linearly. This demonstrates that at the higher frequency part, the ac loss heating, which is proportional to f, is more pronounced. For the test coil used here, an extra part of the ac losses, the vortex loss, which is not included in the simulation may also be significant at the higher frequency part [3].

DISCUSSION

From the simulation and experimental results, it is demonstrated that in an HTS coil, the quenching process can have two steps. The coil maybe heated up by disturbance and ac losses. As the temperature rises, the current sharing starts at the section where $I_c <= I_w$. Then the first step of quenching begins. Since the resistivity of the sheath metal is low at low temperatures, the increase of the resistance due to current sharing is not obvious. Despite of this, the sections where the current sharing happens and the adjacent area will be further heated and this will finally lead to a dangerous heating up if the cooling conditions are not very good. This is the second step of quenching. To avoid it, the protecting system must be started before the coil loss its thermal stability. However, it is difficult to detect by common methods if there are only a few sections in the coil start to lose their superconductivity. From our results, a key point which can help in such detection is a pronounced oscillation of the voltage across the coil at I_w close to I_c', especially when the coil is connected to a power source running in current constant functions. Besides this, the calculated total resistance is also an evidence for the first step of quenching because that in most metals, the resistivity is proportional to the temperature, if the coil is heated up by current sharing, its resistance will rise continuously, although maybe very slowly. Based on these criteria, the I_c' of the test coil used here was detected manually as described above.

CONCLUSION

In this paper, a two-step model of the quenching in the HTS coil was suggested. The heat accumulation comes from ac losses and current sharing was attributed for the quenching development in the coil. According to the modeling and the experimental results, a possible method to detect the first step of quenching was developed, which can be helpful in the power usage of the ac HTS coils.

ACKNOWLEDGEMENT

This work was supported by Chinese National Fund of Sciences, grant No. 50137020.

REFERENCES

1. Wang, Y. S., Zhao, X., Xu, X., Xiao, L. Y., Lin, L. Z., Lu, G. H., Hui, D., Dai, S. T., Angular and Magnetic Field Dependence of Critical Current Density of Multifilamentary Bi-2223 Tapes, Supercond. Sci. Technol. (2004) 17 705-709
2. Li, Y., Li, X. H., Song, N. H., Xiao, L. Y., Numerical study on stability of HTS coil under high pulse currents, Chinese J. of Low Temp. Phys. (2004) 26 76-80
3. Zhang, G. M., Lin, L. Z., Xiao, L. Y., Qiu, M., and Yu, Y. J., The angular dependence of ac transport losses for a BSCCO/Ag tape in dc applied field, IEEE Trans. on Appl. Superdond. (2003) 13 2972-2975
4. Li, X. H., Chen, G., Li, Y., and Xiao, L. Y., Evaluation of the stability profile for a HTS coil by numerical simulation, to be published