Peculiarities on voltage – current characteristics of HTS tapes at overloading conditions cooled by liquid nitrogen

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Abstract. Electro - technical devices are considered as the most prospective use for high temperature superconductors. For such devices the overload currents due to faults in grids are the operational reality. In these cases the fault currents may forcibly go to superconductors being sometimes dozens times more than the critical currents of HTS. Overloads are the working modes for fault current limiters also. To understand the behavior of HTS devices at overloads it is important to study voltage-current characteristics (VCC) of basic HTS tapes in real cooling conditions. The knowledge of VCC permits to model and to simulate properly HTS devices behavior at overloads. We performed the study of VCC of several HTS tapes at currents several times more than their critical ones. Both, 1-G and 2-G tapes were tested. There were found peculiarities or “spikes” on VCC at rising currents that vanished at decaying currents. It was shown that such peculiarities are determined by the change of cooling conditions by the boiling liquid nitrogen.

1. Introduction
Voltage – current characteristics (VCC) are the basic parameters to describe the behavior of any superconductors or devices made of certain superconductors including HTS. Just adequate critical current definition starts form VCC measurements. It is important to know VCC above critical currents also, especially for electro – technical devices made of HTS. Current overloads due to fault in a grid are the operational reality in any power devices. In these cases the fault currents may forcibly go to superconductors being sometimes dozens times more than the critical currents of HTS. Overloads are the working modes for such important devices as fault current limiters. Thus, the knowledge of VCC at currents sufficiently above critical currents of superconductors is important for understanding and proper modeling of the HTS devices behavior at overloads. We performed the study of VCC of several HTS tapes at currents several times more than their critical ones. Both, 1G and 2G tapes were tested as well as simple copper tapes. There were found peculiarities or “spikes” on VCC at rising currents that vanished at decaying currents. It was shown that such peculiarities are determined by the change of cooling conditions by the boiling liquid nitrogen.
2. Experiments

The experiments were performed with several Bi-based first generation HTS tapes as well as with one YBCO second generation HTS tape produced by Super Power Inc. Triangle current pulses (with sweep rates from 0.25A/s to 60 A/s) or rectangular current pulses (with different durations and plateau current magnitude) were put to samples mounted on the insert. Voltages were recorded by use of potential taps attached to samples. The details of the experiments are presented in [1].

Table 1. Samples tested

| Producer of HTS tapes, brand, year of production | Thickness, mm | Width, mm | $I_c$, A (E=1µV/cm) |
|------------------------------------------------|---------------|-----------|---------------------|
| American Superconductor Corp. (AMSC), High Strength Wire LIW, 1769B2B, 2003 | 0.289 | 4 | 131.5 |
| Sumitomo, CT-OP 22-80, 2004 | 0.22 | 4.3 | 93 |
| Trithor, BL035-2, 2003 | 0.22 | 3.5 | 44 |
| Super Power Inc. SCS4050, 2007 | 0.095 | 4 | 63 |
| Copper tape | 0.5 | 4 | - |

2.1. Voltage current characteristics: triangle pulses.

The typical VCC for 1G samples are shown in figures 1 and 2. One can see the distinctive spikes on VCC during current ramping up. The amplitudes and currents where spikes appear depend on ramp rate. All spikes appear at currents much more than the critical ones. On the way back of the current all voltages are the same independently of ramp rate. Similar spikes were observed in [2, 3].

To find out if the VCC observed are the intrinsic properties of HTS like magnetic flux instabilities or they are connected with cooling conditions (as it was suggested in [2, 3]) we tested the copper tape in similar conditions. In figure 3 one can see quite similar VCC with the exception of non-linearity of HTS VCC. That means cooling condition changes are responsible for VCC peculiarities observed and the phenomenon is thermal in nature [2].

![Fig.1 Typical VCC for two 1G HTS samples at different sweep rates. AMSC (left) and Sumitomo (right).](image-url)
2.2. Voltage: rectangular pulses.

As it was shown in [4] the change of cooling conditions in boiling liquid nitrogen from one phase convection cooling to the nucleate boiling and then to the film boiling is the typical phenomenon. The changes from convection to nucleate boiling are characterized by the nucleate boiling activation and development times. Activation time is just the time when one may expect a spike on VCC at a certain ramp rate. Development time shows how quickly better cooling happens. To study cooling condition changes we tested our samples under rectangular current pulses when the heat release is constant unlike during triangle pulses.

![Fig.2 Typical VCC of the Trithor HTS sample](image1)

![Fig.3 VCC of the copper tape](image2)

The typical voltages time traces during rectangular current pulses are shown in figure 4 (for AMSC 1G HTS tape) and in figure 5 (for Super Power 2G HTS tape) as series of graphs with plateau current gradually rising. The characteristics changes typical for all HTS samples measured are as follows.

At currents below certain limit (for example 180A for AMSC sample \( \leq 1.2 \ I_c \), figure 4a) the voltage is rising within a stable mode [5]. Then, the when total heat release forces cooling to switch to the nucleate boiling, voltage becomes completely stable due to the good cooling. Activation time is about seconds or tens of seconds. The initial stable mode has been observed for other 1G HTS samples as well. For example in the Trithor tapes initial stable mode has been observed up to currents \( \sim 2-2.2 \ I_c \), because these old samples have lower overall current density. In 2G HTS sample we did not observed initial stable mode due to higher current density in this tape and, therefore, higher heat release.

At most samples at currents up to \( \sim 3.2 – 3.5 I_c \), (figures 4b, 4c and 5b, 5 c) before nucleation boiling activates the voltage is in unstable regime [5] with the tendency to the fast rising. Activation time drops up to 0.15-0.07 s. This activation time is small enough to switch the cooling to the nucleate boiling and drop the sample to the stable mode.

At currents 3.2 – 3.5I_c and more, (figures 4c and 5 c) even fast drop to the nucleation boiling is not enough to keep balance between cooling and heating and unstable regime takes place with the very fast rising voltage. The danger of this regime is that cooling passes through nucleate boiling to the film boiling with sharp drop of cooling. In this case quick overheating is possible with destroying of an HTS device.

To summarize these data we can conclude that generally the behaviour of HTS tapes at overload conditions follows to ideas developed in [5]: there are two regimes – stable and unstable depending on heat release and cooling balance. At the beginning of the process the convection cooling is not enough to keep voltage/temperature stable even at rather low currents. But with rise of the heat release the nucleate boiling activates and much better cooling returns voltage/temperature to the stable regime even at rather high currents. Then again unstable mode will happens with the rise of currents.

Very typical is the change of regimes from stable to unstable with very small current changes [5]. In figure 5c one can see that change of current from 223 a to 224 A (less than 0.5%) leads to change
from the stable to the unstable mode.
The important characteristic of the process is the sum of nucleate boiling activation and development times that shows the time margin before overheating happens.
3. Discussion

The nucleate boiling activation and development times are depending on heat release mainly but many other parameters, including surface of a sample, space orientation of a tape etc. are important. It is reasonable to find out them experimentally for better estimations.

Dependencies of nucleate boiling development time on heat release are shown in figure 6 for 1G samples. One can see that at heat releases above 30 kW/m² this time is about 0.23 s and then changes weakly. For 2G sample boiling development time was found below 0.1-0.15 s for all currents measured.

Dependencies of nucleate boiling activation time on heat release are shown in figure 7. One can see the drop of the activation time with rise of heat release, or in other words with rise of currents. When heat release exceeds the value ~ 15 kW/m² the fast drop of this time is observed for some samples. It is connected with the transfer from nucleate boiling to the film boiling and with the change of the cooling process from stationary to non-stationary [4]. The heat release ~15 kW/m² is the characteristic pick nucleate boiling magnitude for liquid nitrogen [6].

Considering the data in figure 7, we can conclude the follows:

- At high currents (that corresponds to the high heat release more than 15-25 kW/cm²) the current overload time (or current rising time) should be less than the times shown in figure 7. In this case an HTS conductor or device will be safe from overheating.
- At lower current, when heat releases are below 15-25 kW/cm² an HTS device will be safe during longer times (actually the sum of activation and development time) because after this time the cooling will switch to the nucleate boiling and to the stable state when all heat released will be removed by nucleate boiling cooling.

The safe area for an HTS device is below or to the left from the dotted lines in figure 7. This is the practical conclusion we can make from the measurements of VCC.

Another conclusion is: if the characteristic time of the current ramp rate is less then the activation time of the nuclear boiling one have to take into account the upper branch of VCC shown in figures 1-2. In the opposite case the lower branch of VCC should be used in analysis and calculations.

4. Conclusion

Peculiarities on VCC were studied with several HTS wires at boiling liquid nitrogen cooling. It was shown that they have thermal nature and connected with the change of cooling conditions from...
convection to nucleate boiling. The characteristics times of the process development were determined that is important for design of HTS devices at overload conditions. The data obtained can be used in simulation of heating of real superconducting devices at overload conditions also.

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