Analysis of transient state in HTS tapes under ripple DC load current

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Abstract. The paper concerns the analysis of transient state (quench transition) in HTS tapes loaded with the current having DC component together with a ripple component. Two shapes of the ripple were taken into account: sinusoidal and triangular. Very often HTS tape connected to a power electronic current supply (i.e. superconducting coil for SMES) that delivers DC current with ripples and it needs to be examined under such conditions. Additionally, measurements of electrical (and thermal) parameters under such ripple excitation is useful to tape characterization in broad range of load currents. The results presented in the paper were obtained using test bench which contains programmable DC supply and National Instruments data acquisition system. Voltage drops and load currents were measured vs. time. Analysis of measured parameters as a function of the current was used to tape description with quench dynamics taken into account. Results of measurements were also used to comparison with the results of numerical modelling based on FEM. Presented provisional results show possibility to use results of measurements in transient state to prepare inverse models of superconductors and their detailed numerical modelling.

1. Introduction
Development of high temperature superconductors (HTS) results in continuous progress in manufacturing of HTS wires and tapes. Application of new structure of wire in power devices needs its characterization, especially for quench and stability. The most simple are tests of wire under DC load to measure the critical parameters. Two main drawbacks of this type of measurements are important. The first one, the high power is needed. The second drawback is possible destruction of wire due to long-time quench. These can be eliminated using measurements of short time pulse. This method is well known and used for testing both LTS and HTS wire [1], [2].

The authors decided to carry out the second method as they wanted to make the measurement with various shapes of ripple. Measurement under pulse load allows to determine an influence of AC current on additional AC losses. Since superconductors is loaded with DC current with AC ripple component are widely used, e.g. SMES coils or DC transmission cable authors of this paper present results of HTS tapes such type of load.

An important reason to undertake measurements of HTS tapes under such loads is the need of its parameters for modelling. Detailed analysis of processes occurring inside of HTS tape during its operation, particularly during a quench, can be described by FEM modelling [4].
The main difficulty during development of the numerical models is to determine the material parameters. Correctness of introduced material parameters influences directly on accuracy of the results of numerical analysis. Measurements can be used to improve numerical modelling based on direct models. The result of measurements can be also used to develop inverse numerical models.

2. Measuring and control system

Presented in the paper results were obtained using measuring system shown in Fig. 1, for the sample tape (2) depicted in Fig. 2. The results presented in the paper are carried out for superconducting 1G Bi-2223 sample tape (2) made as two bifilarly arranged tapes with the length of 1 m each. The current was measured by means of the shunt resistor (3). Signal of the current taken from the shunt was sent to DAQ SCXI (5) via terminal (4). The voltage signal was taken from the sample tape and sent to DAQ SCX converter (5) via SCXI terminal (4).

![Figure 1](image1.png)

**Figure 1.** Block scheme of measuring system, 1 - programmable DC current supply, 2 - bifilar HTS tapes, 3 - shunt resistor, 4 - SCXI terminal, 5 - DAQ SCXI converter, 6 PC, 7 - RS 485 link.

![Figure 2](image2.png)

**Figure 2.** Photograph of bifilar HTS tape shaped as spiral.

The second part of the measuring system was a control system of programmable DC current supply. The supply (1) was controlled by LabView user interface using RS-485 interface (7). The DC current supply has over-voltage protection and limited output power. When the voltage along the HTS tape increased above the limit, the output current was reduced. The output power was limited to 1.2 kW. Photograph of the whole system is shown in Fig. 3.

![Figure 3](image3.png)

**Figure 3.** Photograph of the laboratory set-up for control and measurements (HTS tape inside of cryostat immersed in LN2).
3. Results of measurements for sine and triangle ripple of current components

The superconducting tape was immersed in LN2. The voltage drop along the tape was measured versus time. The measurements were carried out for the non-zero positive current in the tape (it means a peak-to-peak amplitude no higher than a twice of DC component).

The comparative measurements were carried out for different maximum current (the minimum value was fixed as a constant), different frequencies (0.5 Hz, 1 Hz and 2 Hz) and different ratio of rise to fall time at triangle ripple. Results of measurements under sine and triangle pulse of current are presented in Fig. 4. Maximum and minimum value of current of both shapes are the same ($I_{\text{max}} = 180\, \text{A}$, $I_{\text{min}} \approx 10\, \text{A}$).

![Figure 4. Quench measured under sine (left) and triangle ripple (right) at 1 Hz.](image)

As one can observe the voltage at rising sine current is different than during falling one (the symmetrical pulse of current results with unsymmetrical voltage), what is the influence of a local temperature on the critical current density (and equivalent resistivity of the tape). The local resistivity is an important parameter of the tape used for numerical (FEM) modelling [3]. Since resistivity is a function of voltage and current the results of the measurements were presented in a form of voltage vs. load current for sine (Fig. 5) and triangle (Fig. 6) current pulse.

![Figure 5. Voltage drop at sine ripple current of 0.5 Hz, 1 Hz and 2 Hz.](image)

![Figure 6. Voltage drop vs. current with triangle ripple, var. rise/fall time rat., 1 Hz.](image)

The results in Fig. 5 shows non-linear dependence between voltage and current (an equivalent resistivity of the tape varies with the current). The resulting voltage vs. current forms a loop during rise and fall of the current. It is due to thermal capacity of the tape. The results given in Fig. 6 shows that equivalent resistivity of the tape depends additionally on current rate of rise. At the same frequency and different rise/fall ratio the voltage is different at the same current. The best results (the smallest loop area) were obtained at rise time equal to fall time.
4. Numerical modelling and future directions of research

The authors developed numerical FEM modelling based on ANSYS software [4]. Transient state modelling allows to calculate spatial and terminal parameters of superconductor (current density, temperature, voltage drop). Example geometry of 1G wire and resulting spatial distribution of the power losses is shown in Fig. 7. The voltage generated under the sine current pulse, shown in Fig. 8 is similar to the waveforms presented in Fig 4. In order to obtain results of numerical modelling reflecting real operation of given structure of HTS tape, the input parameters (material properties) must be corrected.

The results of measurements presented in above sections allows to calculate selected equivalent parameters of the tape, particularly resistivity and thermal capacity. It allows to obtain proper results of numerical modelling for tested HTS tape. Note, that numerical modelling allows to obtain more detailed results than measurements.

![Figure 7. 2D mesh of FEM model (top) and distribution of power losses (bottom)](image)

![Figure 8. FEM results - voltage under sine pulse of current; quench at 42 s](image)

5. Conclusions

Presented in the paper results were obtained for HTS 1G tape carrying DC current with sinusoidal and triangle ripple. The results were presented averaging for several periods of current. Measured voltage drop under ripple load allows to calculate equivalent parameters of HTS tape. Results of measurements at rising and falling current allows to estimate parameters for inverse FEM model of superconductors, also in the part of thermal parameters. Future work will be directed to prepare FEM computational models of superconductors taking results of measurements (measured equivalent parameters) into account.

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