Effect of a superconducting coil as a fault current limiter on current density distribution in BSCCO tape after an over-current pulse

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Abstract. The development of power transmission lines based on long-length high temperature superconducting (HTS) tapes is complicated and technically challenging task. A serious problem for transmission line operation could become HTS power cable damage due to over-current pulse conditions. To avoid the cable damage in any urgent case the superconducting coil technology, i.e. superconductor fault current limiter (SFCL) is required. Comprehensive understanding of the current density characteristics of HTS tapes in both cases, either after pure over-current pulse or after over-current pulse limited by SFCL, is needed to restart or to continue the operation of the power transmission line. Moreover, current density distribution along and across the HTS tape provides us with the sufficient information about the quality of the tape performance in different current feeding regimes. In present paper we examine BSCCO HTS tape under two current feeding regimes. The first one is 100A feeding preceded by 900A over-current pulse. In this case none of tape protection was used. The second scenario is similar to the fist one but SFCL is used to limit an over-current value. For both scenarios after the pulse is gone and the current feeding is set up at 100A we scan magnetic field above the tape by means of Hall probe sensor. Then the feeding is turned of and the magnetic field scanning is repeated. Using the inverse problem numerical solver we calculate the corresponding direct and permanent current density distributions during the feeding and after switch off. It is demonstrated that in the absence of SFCL the current distribution is highly peaked at the tape center. At the same time the current distribution in the experiment with SFCL is similar to that observed under normal current feeding condition. The current peaking in the first case is explained by the effect of an opposite electric field induced at the tape edges during the over-current pulse decay, and by degradation of superconductivity at the edges due to penetration of magnetic field in superconducting core during the pulse.

1. Introduction

The next advance in world electric power supply systems is the use of long-length HTS tapes in electric power transmission cables to transport large DC currents. Long-length cables, in this way, are supposed to suffer the extreme environment and hence the fault conditions are expectable [1]. Due to human factor and technical errors during the manufacturing and maintenance of power transmission line the current transport properties of the line could be affected as well. One of the critical events that could happen is the high over-current pulse, as a result of short circuit, with current value exceeding the critical current of HTS tapes [2, 3]. In this case the operation of the line should be either stopped and then restarted or continued if any protection was used. In this case the complete knowledge of current redistribution in HTS tapes is of high importance to undertake the future actions.
In our study we put BSCCO HTS tape in extreme operating regime, i.e. we apply the over-current pulse reaching 900A current value with the duration of 5ms. After that the current feeding is set up at 100A transport DC for 1 hour. We consider two different operating scenarios, one is the over-current pulse acting on the unprotected HTS tape, and the other is the same pulse acting on the tape protected by means of superconducting coil technique SFCL.

After the pulse is gone and the transport current is set up to its constant value of 100A we provide magnetic field scanning above the tape with use of Hall probe. When the scanning is finished we turn off the power supply simulating the urgent shut down of power transmission line and repeat the scanning of the magnetic field again. In order to obtain current distribution in HTS tape we developed MATLAB code that solves inverse problem and calculates the current density distribution from the magnetic field dataset [4-6]. The detailed analysis of the current distribution demonstrates the essential difference of the current flow in unprotected tape and HTS tape protected by SFCL.

2. Experiment

2.1. Experiment set-up

The experimental setup consists of an open cryostat in which a Hall probe and scanning system, HTS tape and fibre reinforced plastic (FRP) plate as shown figure 1(a) are mounted. For the experiment we use the BSCCO HTS tape [6] with $I_c=200$ A critical current fixed on the FRP plate. The Hall probe (HHP-VP, AREPOC s.r.o) has an active area of 0.05 x 0.05 mm$^2$ and a sensitivity of 49.7 mV/T at 10 mA with the sampling time of 1 second. It is positioned at 200 µm above the tape surface and a stepping motor with the accuracy 0.05 ±0.0025 mm per step controls the Hall probe position across the tape. Both the HTS tape and the Hall probe sensor are directly cooled using liquid nitrogen. On Fig. 1(b) the geometry of experimental configuration with the Hall probe, HTS tape and the current direction are shown. The current is running in the X direction along the tape, and the Hall probe moves in Y direction across the tape. The Hall probe measures vertical $B_z$ component of the self-magnetic field. Usually during the experiment the Hall probe is positioned at the middle of the HTS tape in X direction [7].

![Figure 1. (a) Photo of Experimental device. (b) Experimental configuration.](image-url)
The electric circuit of the experiment is shown in figure 2. A DC power supply (DCPS) has its own switch and current controller, and the maximum DC current of the DCPS is 100 A. DCPS is connected to a shunt resistor and current transducer (CT) to measure the current. A mechanical switch is connected to the circuit, and it is a no-fuse-breaker (NFB) switch. The electric circuit can provide current feed operations simulating the over-current pulse operation and we have a possibility to use a superconducting coil to protect the circuit by smoothing the over-current pulse. On figure 3 the SFCL is presented.

![Electric circuit used in the experiment.](image1)

The SFCL used in our experiment is made by a 27.6 m long of BSCCO wire with Ic=160 A. SFCL inductance is 0.67 mH. The coil is fixed inside a cryostat holder filled with liquid nitrogen. We use pomp to pomp out the air inside the holder. This operation changes the nitrogen state from liquid to solid nitrogen. The superconductor coil then can support the heat generated from the short over current pulse and protect the HTS wire.

The over current pulse in very beginning generates an inductance, which by it’s turn generates number of oscillations in the electric circuit. If we take into account the inside value of the DCPS we can compare our circuit to a normal LCR circuit. The oscillations period is then proportional to the SFCL inductance combined with the inside value of the DCPS capacitance.

![Photo of the Superconductor Fault Current Limiter (SFCL) device](image2)

![The current waveform of the over-current pulse with coil circuit.](image3)
2.2. Over-current pulse operation

This operation simulates the fault current condition. At first the NFB is open, the DCPS is set to 100 A where its voltage is maximum at 5 V according to the power supply controller. When the NFB is switched on, the zero resistivity of the HTS tape allows an over-current pulse to reach 900 A for about 5 ms, then the current is regulated at 100 A by the DCSP after some oscillations within 0.1 s. This evolution of the current is shown on Fig. 4 with red color. The accuracy of the current controller is better than 0.1%. HTS tapes are maintained in liquid nitrogen temperature, important to cool tapes after pulse, by continuously refilling the open cryostat. The peak current is ~900 A, whereas the critical current of the BSCCO tape is 200 A. Therefore, the HTS tape matrix, which is copper and silver with resistivity $\approx 10^{-9} \Omega m$ at liquid nitrogen temperature, carries the majority of current during the pulse [8].

2.3. Normal operation

In order to study the effect of SFCL on the experimental circuit and on the HTS tape performance we add to a circuit a superconducting coil of 0.6 mH shown in figure 3. Then we reproduce the same experiment of the over-current pulse. The oscillations of the feeding current during the first milliseconds is this case are shown on figure 4 with blue colour. As one can see instead of high over-current peak the oscillations of the current around 100 A value and further stabilization to a constant value of 100 A take place. Hence adding the superconducting coil to the circuit eliminates the over-current pulse. The current feeding in this case is equivalent to that is a normal current feeding when the transport current is rising to the value 100 A by 1 A/s steps.

3. Experimental results and Analysis

3.1. Self-magnetic field and permanent magnetic field measurement

The measurements of magnetic field induced by the transport current above the tape are performed for 100A constant current feeding. The Hall probe is moved across the tape in Y direction and along the tape in X direction in order to obtain 2D magnetic field map above the curtain segment of HTS tape. Then we cut the current completely and we repeat measurements for the magnetic field induced by permanent current. The knowledge of the permanent current value gives us the information about the power stored in the transmission line after the shut down procedure.

![Figure 5. Self-Magnetic field profiles of the BSCCO tape after over-current pulse (with and without coil).](image)

![Figure 6. Permanent magnetic field (B0) profiles of the BSCCO tape of normal (with and without coil) and over-current operations.](image)
On figure 5 the vertical components $B_z$ of self-magnetic field after the over-current pulse passed are demonstrated. Two sets of curves are related to the cases with and without over-current coil application. In case when SFCL is not used the magnetic field maximum and minimum absolute values are higher then in case of application of SFCL. Moreover, the peaks are shifted towards the tape center that is evidence of peaked current density profile.

The magnetic field profile related to the SFCL application reflects the fact that current density profile has a flattening and expanded through the tape width. Also we can see that the magnetic field is less homogeneous along the X direction for the pulse-affected tape then for the case of coil application. We predict the over-current pulse effect on the current density homogeneity inside the BSCCO tape.

The figure 6 shows the permanent magnetic field $B_z$ measurements. Even the over-current pulse duration of 5 ms we can see that it has an effect on the permanent magnetic field after cutting the feeding current. The permanent magnetic field is also almost 8 times higher after the over-current pulse without SFCL protection. The effect of the superconducting coil to eliminate the over-current pulse and its effect on current flow in HTS tape is obvious that is also confirmed after cutting the feeding current.

3.2. Current density calculation

In order to get the current density profile of the HTS tape from the magnetic field dataset, we have to solve the inverse problem. In order to do that the MATLAB code with several calculation methods was developed. It is described in details in the references [5], [9]. Here we briefly outline that we use the solver for the set of linear equations that are obtained from the Biot-Savart law. And for the solution we use Cramer's rule.

We use 35 data points of the self-magnetic field and solve for 35 points of current density, assuming the self-magnetic field is constant in time. The measurement time of these 35 data points of the self-magnetic field is 2 minutes; therefore the total current changes by 1.65 % during the measurement is acceptable error. If we assumed that the self-magnetic field profile is constant to solve the equation, the calculation result would be within the measurement error. For solving the inverse problem, we also used a constraint that the total current is 100 A.
The transport current density profiles of the BSCCO tape for both cases with SFCL and without SFCL are shown in figure 7. As shown in the figure the current density after the over-current pulse is peaked at the center. The current is almost conducted by the center of superconducting filaments. The effect of the over-current pulse could be explained by an opposite electric field that is inducted near the tape’ edges during the pulse decay phase. Additionally high current causes magnetic field penetration in the superconducting core of the tape that resulting in superconductivity degradation at the edges. That is the explanation for the peaked current profiles [8].

After applying the superconducting coil is to eliminate high over-current pulse the effect of the pulse as opposite electric field and superconductivity degradation on the edges is eliminated as well. The permanent current density profiles are presented in figure 8. As one can see the current stored in HTS tape after switching of the transport current is much larger in case of over-current pulse effect. The center positive and edge negative current values are almost 10 times higher then in case of eliminated over-current pulse. This is important fact that should be taken into account solving the problem of the restarting power transmission line after emergency shut down. The negative current density at the edges is much more important also for the after pulse phase however this considerably eliminated after adding the over-current pulse and the permanent current is then distributed along all the BSCCO tape.

The inhomogeneity of the magnetic field and also the permanent magnetic field are in agreement with the calculation of the direct and permanent current densities as shown in figure 7 and figure 8. The distribution of the current density in the BSCCO superconducting filament is not equal that leads to different of the current density distribution in the BSCCO tape along the tape’s length. However for the normal operation or by using the superconducting coil to eliminate the over-current effect on the tape we have a homogenous current density distribution.

The electric circuit used in this paper simulated also the basic circuit of the current power coverture [10]. The inductor component acts, in such circuits, as a current source, discharging current (which can be relatively high) that flows through the circuit as the magnetic flux collapses and protect then the circuit from over-currents. Current power coverture is characterised then by a high inductance. Our superconductor coil, which has also a high inductance, can be effective in such role.

4. Conclusion

The superconductor coil was used to eliminate the over-current pulse and hence to protect the electric circuit. Even that the critical current of the coil’s tape is 160A, our experiment show that this technique of SFCL has the effect to delete the pulse. At the very beginning of the pulse the induction of the coil has an effect eliminating the opposite current, and even that the current shows some oscillations in the electric circuit, current densities show homogeneous and uniform current density distributions. These characteristics have a direct and important effect on the DC current distribution on superconductor cables transporting DC current. Also as we know the permanent current also has a result on different phase of DC current feeding. The use of SFCL as we show in our paper helps eliminating any effect of the over-current pulses on the permanent current distribution and then on the next current feeding phases.

5. References

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