Simulations of the quench-behaviour of coated conductors with hot-spots

Alexander Henning, Michael Kurrat
Technische Universität Braunschweig, Institut für Hochspannungstechnik und Elektrische Energieanlagen, Schleinitzstrasse 23, D-38106 Braunschweig, Germany
E-Mail: Al.Henning@tu-bs.de

Abstract. The calculated results of thermal-electric simulations of coated conductors with hot-spots are presented. Multiple 3D-simulations were made with and without hot-spots. As boundary conditions Liquid Nitrogen (LN$_2$) cooling and an overcritical current density are used. The design of the model is based on actual commercial available 2$^{nd}$ Generation High-Temperature-Superconducting (HTS) tapes. The commercially available 3D finite element program ANSYS®, which was enhanced with a superconducting element, is used for the simulations. This work will help to clarify the quench behaviour of HTS-tapes with hot-spots and is especially interesting for current limiting applications.

1. Introduction
The electrical resistivity of high temperature superconductor materials depends on the parameters temperature, current density and external magnetic field. Superconducting Fault current limiters (FCL) are using these dependencies. The most common type of FCL – the Resistive Fault current limiter – utilizes the transition from the superconducting state to normal conducting state if the current exceeds the critical current of the superconductor during a short circuit. While operating normally, the current density in the superconducting material is well below the critical current density – the FCL is superconducting. During a short circuit the current exceeds the critical current, causing a very rapid increase of the electrical resistivity and therefore a very rapid rise of the temperature too. Through this increased series resistance the current flow in the circuit is limited. The limitation process is a complex interaction between the current flow influenced by the current- and temperature-dependent resistivity, the temporal and local temperature evolution of the high temperature superconductor (HTS), its substrate and the external circuit [1,2,3]. Since it is not possible to produce perfect homogenous HTS-tapes, it is not possible to avoid the occurrence of areas with a lower critical current density – so called hot spots. It is generally known, that these hot-spots could cause local overheating and possible destruction of the superconducting layer. In this work a model of an 2$^{nd}$ Generation HTS tape based on AMSC’s 344S tape was used in simulations with an overcritical current.

2. Simulation Setup
For the simulations the commercially available 3D finite element program ANSYS®, which was enhanced with a superconducting element, is used. The equations used to program the coupled dependencies of the electrical resistivity on temperature and current density are:
1

E is the electric field, $E_C$ the critical electric field, $J_C(T)$ the temperature-dependent critical current density, $m$ and $P$ are constants which are material-specific but not temperature-dependent. Additional details on the programming can be found in [4] and [5].

2.1. Simulation Model

The model-geometry used in the simulations is based on AMSC’s 344S 2nd Generation HTS-tapes. A cut-out view of the simulation model is shown in figure 1. To make the model-building easier instead of a multi-buffer-layer system only layer was used.

As shown in figure 2 the HTS tape modeled in the simulations was 4 mm wide in y-direction and quasi-infinite in x-direction (direction of current flow). The hot-spot used in the model had a size of 1% of the total area and a critical current density $J_{C2} = 2 \times 10^5 \text{ A/cm}^2$ while the critical current density of the remaining YBCO was $J_{C1} = 2 \times 10^6 \text{ A/cm}^2$. The critical temperature was set to $T_C = 88 \text{ K}$. In addition the surfaces of the wire were cooled by liquid nitrogen (LN2).

To make the model building and the FEM-mesh somewhat easier the MgO buffer layer was modeled 10 times the original height (4µm instead of 400nm) with an adaptation of the material parameter in z direction. Furthermore to conserve computing time the symmetry of the model was utilized, with an adaptation of the LN$_2$ cooling boundary condition at the symmetry axis. The resulting model with was therefore 2 mm.

The same model was simulated multiple times with and without the hot-spot and with different currents to compare the behaviour of homogenous and inhomogeneous materials. The current flowing...
during the simulation was quantified as a boundary condition (constant DC-current flow) with different values of $I/I_{C1} = 1.5$, $I/I_{C1} = 2$ and $I/I_{C1} = 3$. The current density used to calculate $I_{C1}$ was $J_{C1} = 2 \times 10^6 \text{ A/cm}^2$.

For evaluation temperature, current density, heat generation per volume, thermal flux density, electric potential and the electric field strength were mapped onto four paths (Figure 2). All paths were made in minus z-direction from top to bottom of the model. The first path (1) was located between the inner structure and the perpendicular Sn-layer, the second path (2) in the middle of the homogenous part. The third path (3) is located at the edge of the hot spot and the forth path (4) in the middle of the hot-spot at the symmetry axis. In the following the simulations with the weak part in the HTS will be called inhomogeneous and the simulations without the weak part homogenous.

3. Results

Figure 3 shows current density in the HTS-layer at the location of the path 3. It can be seen that the current density in the inhomogeneous simulations is one order of magnitude lower than in the homogenous ones. Additionally the critical temperature $T_C = 88 \text{ K}$ is clearly visible. This confirms the correctness of the simulation.

In figure 4 the temperature development over time is shown. With the exception of the simulations with $I/I_{C} = 1.5$ there is nearly no difference between the homogenous and inhomogeneous model ($\Delta T < 1 \text{K}$) in the heating of the material over time. The maximal temperature difference of the two curves with $I/I_{C} = 1.5$ is $1.48 \text{ K}$. Since even hot-spots with a much lower critical current density have no remarkable effect on temperature development, it can be said, that a coated conductor system with a good thermal and electrical coupling between the single layers has very few problems with local overheating because of hot spots.

Another important thing to consider during the development of 2nd generation HTS-tapes is the electrical coupling of the layers. Especially if an insulating buffer layer is used. Since the current has to commutate into the substrate layer during quench of the superconducting layer there is a possibility of high electrical field strengths with resulting flashovers in the insulating buffer layer. One potential solution of this problem may be the use of conductive buffer layers as presented in [6, 7]. Another is a good electrical coupling of the different layers. The layers in the simulation model used in this work are coupled with a 75 µm thick tin-solder layer. Therefore a good electrical coupling can be assumed. Figures 5 and 6 show the typical progression of the electrical field along the evaluation paths described earlier (figure 2) for a maximum temperature of 100 K ($I/I_{C} = 3$) and for 88 K ($I/I_{C} = 2$) in the model. The maximum electrical field of all simulations is about 83 V/m with $I/I_{C} = 3$ at a temperature of 100 K. Since maximum occurring electrical field of 83 V/m is well below the electrical breakdown strength of solid state material, which is generally in the kV/mm range, it can be concluded...
that because of the good electrical coupling of the different layers no flashover is to be expected. In no simulation the electrical field strength exceeded 83 V/m.

Figure 5 Electrical field along all four paths inhomogeneous model with maximum temperature of 100 K and with \( I/I_C = 3 \)

Figure 6 Electrical field along all four paths homogenous model with maximum temperature of 88 K and with \( I/I_C = 2 \)

4. Conclusions
In this paper the influence of weak parts, so called hot-pots, in the HTS-layer of 2nd generation superconducting tapes is investigated. In addition the distribution of the electrical field over the different layers of coated conductors was examined. In conclusion it can be said, that coated conductors with good shunting and a good electrical coupling have no problems with flashovers inside the material and very few problems with local overheating because of local weak parts inside the superconducting layer.

5. Acknowledgment
The authors would like to thank the Institut für Oberflächentechnik of the Technical University Braunschweig for help. The help of Ansys Inc. USA by supplying the element codes for the FEA program ANSYS® is greatly acknowledged.

References
[1] Fischer S., Sämann D, 2000 Supraleitende Strombegrenzer – Eine Revolution in der Energietechnik? Elektrizitätswirtschaft 25/2000.

[2] Schubert M., 1997 Untersuchungen über den Einsatz von Hochtemperatursupraleitern zur Kurzschlußstrobombegrenzung. Fortschrittsberichte VDI, „Düsseldorf“

[3] Mosebach H., 1999 Schaltverhalten von Hochtemperatur-Supraleiter-Bändern zur Strombegrenzung. „Shaker Verlag, Aachen“

[4] Henning A., Kurrat M., June 2007 Thermal-electric simulations of coated conductors with a variable conductivity of the buffer layer. IEEE Trans. On Applied Superconductivity, Volume 17, Issue: 2 Part 3, Pages: 3443-3446.

[5] Grundmann J., 2007 Kennlinienfeldmessungen und Modellierung der Auslösung und Quenchausbreitung in HTSL-Strombegrenzern. „Doctoral Thesis, Braunschweig“

[6] Stadel O., et.al., 2006 MOCVD of coated conductors with electrically conductive buffer layers and their electrical field. Journal of Physics: Conference Series, UK * 43, no 1, page 207-210

[7] T. Aytug, M.Paranthaman, H.Y. Zhai, A.A. Gapud, K.J. Leonard, P.M. Martin, A. Goyal, J.R. Thompson, D.K. Christen 2004 Appl Phys Letters vol 85 n 14 2887