Dissipated energy as a design parameter of coated conductors for their use in resistive fault current limiters

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Abstract. Coated conductors are suitable for many power applications like motors, magnets and superconducting fault current limiters (SCFCLs). For their use in resistive SCFCLs main requirements are quench stability and resistance development above $T_c$. Several coated conductors are available with different kinds of stabilization like thickness or material of cap-layer and additional stabilization. The stabilization can vary and has a great influence on the quench stability and quench behaviour of a coated conductor. Thus, for the dimensioning of a superconducting current limiting element there is a need of reliable and universal design parameters. This paper presents experimental quench test results on several coated conductor types with different stabilization and geometry. The test results show that the dissipated energy during a quench is a very useful parameter for the SCFCL design.

1. Introduction
Future electrical power networks are getting better cross-linked due to the progressive decentralized generation and coupling of networks for an improved power quality. Consequently the short current levels increase. Superconducting fault current limiters (SCFCL) are favorable devices to avoid high short current levels. The resistive SCFCL with coated conductor as limiting element is one of the most promising types [1]. The advantages of coated conductors are their low mass, high normal conducting resistance, high n-value and high critical current. The first fault current limiters with coated conductors are under development and the first demonstrators are finished [2, 3].

For an optimised design of a SCFCL several design parameters are essential. One is the maximum dissipated energy during short-circuit limitation without a damage or degradation of the coated conductor. This work presents the experimentally determined energy density limits of three different coated conductors from different manufacturers with a length of 11cm. The maximum dissipated energy of the different coated conductors was very different. This is due to their stabilization structure and manufacturing process. The maximum energy density corresponds to a maximum temperature of the coated conductor in reference to the physical properties of the structure materials [4].
2. Test samples
Three types of 11cm long coated conductors with different geometry, structure, critical current and manufacturing process were tested. Table 1 shows the specifications of the coated conductor types. The structures of the coated conductors differ in material composition of cap-layer and substrate, thickness of the different layers and an optional stabilization. The buffer layers are assumed as electrical insulating layers. Therefore, the differences of the structure end in different resistances and thermal properties of the coated conductor.

| Type | \( I_c \) (approx.) | Inhomogeneity (dev. of sectional \( I_c \) from total \( I_c \)) | Thickness (approx.) | Width | Optional stabilization | Resistance / Length @ 296K |
|------|-----------------|-----------------|-----------------|------|------------------------|---------------------------|
| 1    | 140A            | < ±2.2%         | 2.5μm 95μm 0.16μm \(^a\) | 12.4mm | -                      | 3.6mΩ/cm                  |
| 2    | 100A            | > ±7.1%         | 5μm 93μm 4μm   | 9.9mm | -                      | 2.5mΩ/cm                  |
| 3    | 60A             | < ±9.9%         | 1μm \(^b\) 50-70μm \(^b\) 0.23 μm \(^b\) | 4.2mm Stainless steel and solder | 3.3mΩ/cm |

manufacturer's data \(^a\)[3], \(^b\)[5]

3. Experimental setup
The samples were tested with several numbers of sinusoidal over-currents of 50Hz in boiling liquid nitrogen \(^a\). Power source was a one phase transformer with a thyristor-switch on its secondary side with voltage amplitude of 40V. The prospective current amplitudes \( i_p \) were adjusted with a serial resistance to the test sample. The operative serial resistance \( R_V \) is the accumulated resistance of the interior resistance of the transformer, the line resistance and the serial resistance. Thus, the voltage drop over the coated conductor is a result of its temperature dependent resistance and the serial resistance \( R_V \) corresponding to a voltage divider \(^a\). The current and voltages of the over-current measurement was recorded with a transient recorder.

4. Measurement procedure
First the total \( I_c \) over 11cm length and sectional \( I_c \) over every single centimeter was determined with the 1μV/cm criterion to control the functionality of the coated conductor. Some sections of inhomogeneous coated conductors do not reach the 1μV/cm criterion. In this case the \( I_c \) measurement was stopped in order to avoid a damage of the coated conductor. These sectional \( I_c \) values were calculated based on the last measured data by the well known power law \(^b\).

Next, the prospective current \( i_p \) without the superconductor in the circuit was adjusted with the variable resistance \( R_V \) at the beginning of the over-current measurement sequence. The adjusted \( i_p \) is given in the legend of the figures 1, 3 and 5 of each coated conductor type for every test sample. The over-current measurements started with a low number of half-waves in order to avoid a damage of the test sample. Then, the number of half-waves was increased step wise. After each increasing step \( I_c \) was controlled to be sure that \( I_c \) did not degrade or the coated conductor got damaged. A degradation of \( I_c \) of more than 4% was defined as a damage of the coated conductor as well. The test ends after the damaging of the coated conductor. After damaging of the tested sample, the prospective current was decreased and the procedure starts again with a new sample and a larger number of half-waves.

5. Results
The energy is the time integrated product of the measured current and total voltage over 11 cm length. For the energy density is the over-all volume of the test sample used. The results of the energy density measurements are only shown for 4 samples of each type in steps of 20ms for better clearness. There were made more measurements in steps of 10ms with the same results.
5.1. Coated conductor type 1
Figure 1 shows the energy density measurements for 4 samples of the coated conductor type 1. This type shows a consistent degradation of $I_c$. The $I_c$ degradations relating to the origin $I_c$ measurement before any over-current measurement are stated with the percent numbers in figure 1. Our measurements show a maximum $I_c$ degradation of 1.6% (rd. 2.2A) below 2300J/cm$^3$. At energy densities above 2600J/cm$^3$ showed every sample a degradation of more than 4% and was defined as damaged even though the sample was still superconducting. Nevertheless, every test sample of the tested type 1 coated conductor shows a slightly different degradation of $I_c$.

Figure 2 shows an exemplary sectional $I_c$ measurement of the type 1 coated conductors. The total $I_c$ was determined to 140A by the measured total voltage over 11cm. The diagram shows a relative uniformly increase of the measured voltage over eleven 1cm long sections. The sectional $I_c$ deviation related to the mean $I_c$ was lower than +/- 2.2%. Therefore, this coated conductor type can be classified as a homogeneous coated conductor.

5.2. Coated conductor type 2
Figure 3 shows the energy density measurements for 4 samples of the coated conductor type 2. This type shows as well as type 1 a consistent degradation of $I_c$. A significant $I_c$ degradation begins above 680J/cm$^3$. The degradation of $I_c$ was greater than 5.9% at energy densities of more than 820J/cm$^3$ but the coated conductor stays still superconducting. The smooth degradation of $I_c$ can be seen in figure 3 on the sample with the lowest prospective current with more than 10 half-waves. The energy increment per half-wave at this prospective current was too low to reach the energy density of 820J/cm$^3$ in the eleventh half-wave. Thus, $I_c$ degraded first at an energy density of 773J/cm$^3$ (after 11 half-waves) about 2% and then at 885J/cm$^3$ (after 12 half-waves) about 6.2%.

Figure 4 shows a typically measurement of the sectional $I_c$ of the coated conductor type 2. The total $I_c$ was determined in this example to 100A with the measured voltage over 11cm (not shown in the figure). The deviation of the sectional $I_c$ relating to the mean $I_c$ was at least 7.1%. Only a few sections drive into the normal conducting state below 100A in this example. All others stay superconducting at this current. Therefore, this type can be classified as an inhomogeneous coated conductor.
5.3. Coated conductor type 3

Figure 5 shows the measured energy density of 4 samples of the coated conductor type 3. This type 3 had an additional soldered stabilization of stainless steel. Therefore, this type shows a different mechanism of damaging. At energy densities of about 1200 J/cm$^3$, this type showed a sudden total damage of the superconducting layer. The damaging of a test sample can be clearly detected on the measured voltages. There is nearly no degradation of $I_c$ before the total damage as you can see in figure 5. As mentioned before, the energy density corresponds to a temperature of the coated conductor. The energy density of about 1200 J/cm$^3$ corresponds well to the melting temperature of the solder of the additional stabilization.

Figure 6 shows an $I_c$ measurement for a type 3 coated conductor. The determined total $I_c$ was 60 A with the measured voltage over 1 cm. The sectional voltages show a relative uniformly increasing. Therefore, this type can be classified as a homogeneous coated conductor.

Figure 5. Dissipated energy per volume and limit without damage of 4 samples coated conductor type 3 with different prospective currents. (Sample length 11 cm, 77.3 K)

Figure 6. Exemplary critical current measurement of 1 cm long sections of coated conductor type 3 before the over-current test. (Sample length 11 cm, 77.3 K)

Figure 3. Energy dissipation per volume and the degradation of $I_c$ of 4 samples coated conductor type 2 with different prospective currents. (Sample length 11 cm, 77.3 K)

Figure 4. Exemplary critical current measurement of 1 cm long sections of coated conductor type 2 before the over-current test. (Sample length 11 cm, 77.3 K)
6. Conclusions
Several types of coated conductors with differences in structure and manufacturing process are investigated. The energy density at damaging of the coated conductor was determined. The maximum energy densities without damaging are very different for every coated conductor type. The highest energy density reached type 1 with about 2300J/cm³. The two tested type 1 and type 2 coated conductors without solder in the structure showed a smooth progress of $I_c$ degradation. Coated conductor type 3 with an additional soldered stabilization showed a sudden and total damaging of the superconducting layer after reaching an energy density of about 1200J/cm³.

The energy density as an absolute value depends strongly on the structure and the physical properties of the used materials. Consequently, the energy density corresponds to the temperature of the coated conductor taking into account the physical properties of the structure materials [4].

Nevertheless, all of the tested coated conductors had a consistent degradation of $I_c$ or damage at a certain energy density. Therefore, the dissipated energy seems to be an applicable limit parameter for the design of a fault current limiter with coated conductors.

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