Current Capacity of Ag/Bi-2223 Wires for Rotating Electric Machinery

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Abstract. With focus on the application in rotating electric machines we measured the dependence of current capacity of Ag/Bi-2223 wires on temperature and magnetic field. Even for wires stemming from a single manufacturer we observe a significant spread of wire properties. We study different temperature and magnetic field dependence by a parallel path model which allows for a quantitative analysis. The implications of experiments and modelling are discussed with regard to the further wire development and for application within windings.

1. Introduction
Siemens is developing rotating electric machines of MW class using exciter windings with Ag/Bi-2223 wires [1]. A fundamental requirement for the application of Ag/Bi-2223 wires in lengths of several km is the reliable prediction of critical currents at operating conditions within temperatures of 25 – 35 K and magnetic fields up to 4 T. However, wire manufacturers characterize and optimize Ag/Bi-2223 wires with focus on critical current at 77 K and zero external field. Therefore, Siemens has pursued the qualification of wires under operating conditions. Even for wires stemming from a single manufacturer a significant spread of 40 % of the dependence of critical current on temperature and magnetic field has been observed.

In this paper we report on the analysis of current capacity based on a parallel path model which allows for a quantitative assessment of wire properties. The model applies for the entire temperature and magnetic field range and considers all relevant properties. We show that the specific temperature and field dependence of wires results from varying weak and strong link contributions. We discuss the implications of the results for the optimization and application of Ag/Bi-2223 wires.

2. Experimental Techniques and Measurements
Ag/Bi-2223 wires in length of approximately 100 m were provided by five manufacturers A, B, C, D, and E corresponding to state-of-the-art quality. From manufacturer A and B two samples stemming from different batches were investigated. Transport measurements were performed as described elsewhere [2] in a temperature range of 20 K – 110 K and magnetic fields up to 5 T oriented perpendicular to the tape surface. According to the quality control of the manufacturer we denote (77 K, self field) as specified conditions whereas (25 K, 4 T) is regarded as an operating condition typical for rotating electric machinery. The scaling factor $F$ characterizes the ratio of critical currents at (25 K, 4 T) and (77 K, self field). Table 1 lists the wire properties. In Table 1 a spread of scaling factors of 40 % is observed revealing a specific temperature and magnetic field dependence.
Table 1: Transport properties of Ag/Bi-2223 wires from manufacturers A – E.

| Wire | Cross Section (mm²) | $I_c(77 \text{ K}, \text{ SF})$ (A) | Scaling Factor $F$ |
|------|---------------------|-----------------------------------|------------------|
| A #1 | 4.03x0.22           | 75.5                              | 1.37             |
| A #2 | 4.05x0.24           | 93.4                              | 1.11             |
| B #1 | 4.23x0.32           | 129.2                             | 1.56             |
| B #2 | 4.20x0.29           | 153.0                             | 1.28             |
| C    | 4.35x0.24           | 132.7                             | 1.51             |
| D    | 4.14x0.22           | 90.2                              | 1.41             |
| E    | 3.22x0.22           | 47.5                              | 1.13             |

3. Parallel Path Model

Transport properties of Ag/Bi-2223 exhibit apparent features which hint towards two independent parallel current paths which are regarded as a weak link and a strong link path. The signature of the weak link path is a kink in the temperature dependence of critical current around 80 K [3]. For the strong link path a universal scaling behavior has been observed in the high field range [2].

3.1. Weak and Strong Link Paths in Bi-2223 Wires

From the weak and strong contributions $I_{cw}$ and $I_{cs}$ the total critical current $I_c$ is given by

$$ I_c(B,T) = I_{cw}(B,T) + I_{cs}(B,T). \tag{1} $$

The weak link path with a strong suppression by magnetic fields follows from the Kim model [4]

$$ I_{cw}(B,T) = I_w(T) \left(1 + B/B_w(T)\right)^{-1}. \tag{2} $$

In (2) $I_w(T)$ and $B_w(T)$ are given by

$$ I_w(T) = I_{cw0} \left(1 - T/T_{cw}\right), \tag{3} $$

$$ B_w(T) = B_{w0} \left(1 - T/T_{cw}\right), \tag{4} $$

where $I_{cw0}$ is the weak link critical current at 0 K, $B_{w0}$ is a characteristic field and $T_{cw}$ is the critical temperature of weak link path. The strong link path follows from the empirical field dependence [5]

$$ I_{cs}(B,T) = I_s(T) \text{Exp}(-B/B_s(T)). \tag{5} $$

In (5) $I_s(T)$ and $B_s(T)$ are obtained from

$$ I_s(T) = I_{cs0} \left(1 - T/T_{cs}\right), \tag{6} $$

$$ B_s(T) = B_{s0} \text{Exp}(-T/T_{s0}). \tag{7} $$

where $I_{cs0}$ is the critical current at 0 K and $T_{cs}$ is the critical temperature of the strong link path. For the characteristic field $B_s$ an exponential temperature dependence is chosen.

In the literature similar approaches as compared to the model introduced by (1) to (7) have been discussed. However, these earlier approaches assume a more elaborated modelling requiring a huge number of up to 10 variable parameters per specimen [3]. Thus they do not appear as viable for characterisation of a broad range of wires. The aim of our work is to identify universal parameters and to reveal sample specific properties by a minimum set of parameters. The following three steps allow for a reduction down to three variable parameters: (i) The model aims not at the exact field depen-
dence in the mT range since it is not relevant for the application with maximum fields of several Tesla. Therefore, the weak link path is described by a universal value of $B_{w0} = 50 \text{ mT}$. (ii) For the strong link path a universal critical temperature of $T_{cs} = 107 \text{ K}$ is chosen. Different wires may exhibit a variation of $T_{cs} = 105 \text{ K} - 113 \text{ K}$. However, according to (6) this results in a slight correction for $I_{c0}$ of $(1-105/113) = 7\%$. (iii) In [2] a universal scaling of critical currents has been observed in range of high fields. The magnetic field dependence of various wires collapses onto a single curve after normalisation to an in-field value indicating a universal dependence of $B_s(T)$. For sample A #2 $B_s(T)$ is obtained from fitting (5) to $I_c(B)$ curves with $B > 0.5 \text{ T}$ measured for 5 temperatures in the $20 \text{ K} - 77 \text{ K}$ range. With a correlation of 99.6 \% we derive parameters $B_{s0} = 59 \text{ T}$ and $T_{s0} = 13.6 \text{ K}$ for $B_s(T)$. Thus in total the current capacity may be revealed by only three variable parameters, i.e. critical temperature of weak link path $T_{cw}$, critical current of weak and strong link path at 0 K $I_{cw0}$ and $I_{cs0}$.

In the low field range a further correction is required with the total field acting on the wire given by the sum of external field and self field. Motivated by the anisotropy of Bi-2223 we consider the self field by its maximum perpendicular component. For an analytical thin strip with width $w$ and thickness $d$ the maximum component is derived from the field constant $b_{max}$ [6]

$$b_{max} = \left(\frac{\mu_0}{2\pi w d}\right)\left(\frac{d}{2}\ln\left\{1 + \left(\frac{2w}{d}\right)^2\right\} + 2w \arctan\left(\frac{d}{2w}\right)\right).$$ (8)

3.2. Application of the model

In order to test the validity of the model developed in Sec. 3.1 we measured temperature and magnetic field dependence of wires of table 1. Fig. 1 shows (a) temperature dependence and (b) magnetic field dependence for sample A #2. According to the input parameters a set of three measurements is required to fit the model to experimental results. We choose $I_c(77 \text{ K}, \text{SF})$, $I_c(25 \text{ K}, \text{SF})$, and $I_c(25 \text{ K}, \text{B})$ as input data and derive model parameters of $T_{cw} = 88.7 \text{ K}$, $I_{cw0} = 615 \text{ A}$, and $I_{cs0} = 200 \text{ A}$.

The temperature dependence of critical current in Fig. 1a) appears as the sum of weak and strong link contributions which can be nicely distinguished by their critical temperatures of $88.7 \text{ K}$ and $107 \text{ K}$. The kink in temperature dependence at the transition temperature of the weak link path is apparent. Taking into account the self field a major correction for the weak link path is obtained whereas identical curves result for the strong link path. With lower temperatures increasing weak link contributions are observed in Fig. 1a). At $77 \text{ K}$ 43 \% of the critical current stems from the weak link path rising to 60 \% at 25 K. These weak link fractions may not be associated with the volumetric contents of residual Bi-2212 since in [7] a 95 \% Bi-2223 microstructure is reported. This hints that the remaining Bi-2212 is located effectively in the microstructure controlling the flow of inter granular currents. An analysis of this finding may be assessed by local characterization, e.g. EDX analysis.

![Figure 1](image-url)

Figure 1: Measured and modelled (a) temperature and (b) magnetic field dependence for sample A#2.

The magnetic field dependence in Fig. 1b) shows a clear correlation between measured and modeled data. Three field regimes are observed: (i) For $B < 0.05 \text{ T}$ a plateau with constant $I_c$ resulting from the self field suppression of weak link path, (ii) for $0.05 \text{ T} < B < 1 \text{ T}$ a decreasing weak link contribution with a constant strong link background, and (iii) for $B > 1 \text{ T}$ the total fall off of $I_c$ due to
suppression of strong link path. As in Fig. 1a) the self field affects only the weak link path. The existence of two parallel current paths becomes most apparent in the inflection point at 1 T. From Fig. 1b) follows that the weak link path is negligible for fields higher than 1 T with the current capacity of the wire determined by the strong link contribution. With regard to the operating condition of rotating machinery an enhancement of current capacity may be obtained by increasing the strong link content.

3.3. Discussion of Wire Properties

As for sample A #2 the model was applied to all wires of table 1. A spread of model parameters of $T_{cw} = 84.2 \text{ K} - 88.7 \text{ K}$, $I_{cw0} = 280 \text{ A} - 2100 \text{ A}$, and $I_{cs0} = 100 \text{ A} - 390 \text{ A}$ has been obtained. Fig. 2 summarizes the strong and weak link contributions at (77 K, SF) and (25 K, 4 T). As in Sec. 3.2 major weak link contributions are found for all wires at (77 K, SF) which appear as negligible at (25 K, 4 T). The different scaling factors $F$ of Table 1 are easily explained by the varying weak link content within the wires. The highest scaling factor is obtained for sample B #1 showing the lowest weak link contribution at (77 K, SF). The model allows for a classification of samples according to their strong link contributions. Comparable strong link contributions are found for samples A #1, A #2, D and for samples B #1, B #2, C, which exhibit similar current capacity at (25 K, 4 T).

From point of view of wire manufacturer this reveals that the optimization of wire properties for (77 K, SF) does not match the requirements of rotating machinery and that a quality control at (77 K, SF) is not sufficient to guarantee uniform properties. From application side the model can be applied for the layout of windings and to help for a better understanding of experimental results.

Figure 2: Strong and weak link contributions at (a) $T = 77 \text{ K}$, self field and (b) $T = 25 \text{ K}, B = 4 \text{ T}$.

4. Conclusions

We presented a quantitative analysis of current capacity of Ag/Bi-2223 wires based on a parallel path model of strong and weak links. At (77 K, SF) all wires exhibit major weak link contributions whereas at operating conditions of rotating machines the current capacity depends only on strong links.

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