AC loss in superconducting wires operating in a wind turbine like generator

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Abstract. We have manufactured a small circular superconducting coil impregnated with epoxy fibreglass. The coil was wound from a Bi-2223/Ag superconducting wire and it was tested in liquid nitrogen at 77 K. Current-voltage characteristic and the AC losses of the coil were measured and compared with the measurements on the original tape. The AC losses of the coil are approximately 10 times higher than the losses of the tape and they have been measured in two different experimental arrangements, one with directly connected and the other with transformer coupled power supply. Measurements in both arrangements resulted in the same AC loss characteristic. This work was done as a part of the Superwind project which aims to build a series of test coils and a spinning model of a generator to investigate AC loss and stability of the coils in wind turbine like conditions.

1. Introduction

Utilisation of superconducting wires in construction of electrical generators has always been a very attractive possibility for practical application of superconductors \cite{1}\cite{2} and the worldwide interest in this subject has grown especially after a huge progress was achieved on the field of coated superconducting tapes. The work presented in this article is a part of a research project called “Superwind” \cite{3} which aims to develop a design of 10 kW class wind turbine electric generator with superconducting rotor coils. There is an outlook to place the generator in an already existing wind turbine \cite{4}.

Manufacturing and testing of several circular test coils impregnated with epoxy resin is an essential part of the project. It should provide the basic knowledge and experience that will be utilised to construct a spinning model of the electric generator where the racetrack-shaped superconducting coils will be used to generate the magnetic field. AC losses and stability of these coils will be investigated in the wind turbine operation conditions.

We present here the results of the measurements made on our first circular test coil which was wound from the Bi-2223 superconducting wire. We have measured the coil’s current-voltage characteristic (I-V curve) and the dependence of AC losses on the amplitude of the AC current flowing in the coil (AC loss characteristic).
2. Coil manufacturing

Our small circular test coil is wound from the Bi$_2$Sr$_2$Ca$_2$Cu$_3$O$_{10}$ (Bi-2223) multifilamentary wire with Ag matrix laminated with brass at the surface. The tape’s width is 4.2 mm, thickness 0.36 mm and total length of the tape in the coil is approximately 1.1 m. According to the wire specifications its self-field critical current is 145 A in liquid nitrogen (77 K).

The coil is of “pancake” geometry and it was wound by hand on a plastic disk-shaped mandrel of the diameter 35 mm which was screwed to a supporting aluminium plate. In the winding process the superconducting tape was covered with a fibreglass tape on one side. This fibreglass tape provided electric insulation between the individual turns of the coil and it was also mechanically reinforcing the coil’s construction after impregnation with epoxy resin.

The result of the manufacturing process was a self-supported coil with 9 turns in epoxy fibreglass encapsulation. The central puck mandrel has been removed and flat braided copper conductors were soldered on the tape at the internal and external circumference, on the sections that were protected from the epoxy by teflon cover and a slip agent. Figure 1 presents a photograph of the finished coil together with two more illustrating the manufacturing process and a drawing of the coil’s cross-section.

Winding diameter we have used (35 mm) is considerably smaller than the Minimum Double Bend Diameter specified by the tape’s manufacturer which is 50 mm. We decided to test the performance of a coil with dimensions going beyond this limit since the possibility to use smaller bending diameters would be very useful for the design of the model generator. Another reason was to enable future testing of the coil in a liquid helium cryostat which has limited sample space. It is also true that the tape undergoes only a single bending in the coil winding process.

![Image of coil winding process](image)

**Figure 1.** Photograph of the superconducting coil after winding with the fibreglass tape between the turns (a), the coil in a mould filled with epoxy resin in a vacuum furnace (b), finished coil after the impregnation (c) and a schematic drawing of the coil’s winding with dimensions in millimetres (d).

3. Measurements

3.1. I-V curves

Current-voltage curves were measured on both the original Bi-2223 tape and on the coil in the liquid nitrogen bath. Tape measurements were made by a standard four probe method on 8 cm long sample with 1 cm distance between the voltage contacts which were placed in the middle
area of the sample. A homogenous constant magnetic field was applied on the tape during the measurements. In one series of measurements the magnetic field was applied perpendicular and in the second one parallel to the tape’s wide face.

I-V measurements on the coil were made without applying any external magnetic field. The voltage contacts were located near the current leads so the voltage drop over the entire coil’s length was measured.

Figure 2. Current-voltage curve measured on the superconducting coil and a fit to this data by the power law function with the displayed parameters.

The I-V curve measured on the coil is shown in the figure 2 and selected I-V curves measured on the original tape are plotted in the figure 3, together with the coil’s I-V curve. Experimental data measured on the coil can be well fitted with the power law function \( E = E_0 (I/I_c)^n \) with parameters \( I_c = 66.4 \) A and \( n = 11.2 \) (the voltage criterion \( E_0 = 1 \mu V/cm \)).

The comparison of the I-V curves measured on the coil and on the tape (fig. 3) shows that the coil’s I-V curve lies closest to the tape’s I-V curves measured at 40 mT and 60 mT applied perpendicular magnetic field.
We have made a very simple electromagnetic calculation of the magnetic field distribution inside and around the coil with the help of the Comsol software which employs the finite element method. The winding was modelled as a homogenous conducting media with evenly distributed current density. The calculation reveals that the maximum magnetic field at the coil’s surface is approximately 60 mT at 70 A current flowing through the coil (i.e. 9 × 70 A through the winding’s cross-section). More precisely, the maximum magnetic field oriented perpendicular to the wide face of the tape is 52 mT and the maximum magnetic field oriented parallel to the wide face is 68 mT. The calculated distributions of the perpendicular and parallel magnetic field are shown in the figure 4. Here the x coordinate is oriented perpendicular and the y coordinate parallel to the wide face of the tape in the coil.

Critical current ($I_c$) of the superconducting tape is strongly suppressed especially by the perpendicular magnetic field. It’s maximum value in the coil estimated by the calculation, 52 mT, lies between 40 mT and 60 mT which coincides with the observation made from the coil.

**Figure 4.** Calculated distributions of the perpendicular ($B_x$, top picture) and the parallel ($B_y$, bottom picture) component of the magnetic field generated by the coil when 70 A current is flowing through the turns. The $B_x$ component is perpendicular and the $B_y$ is parallel to the wide face of the Bi-2223 tape.
and tape I-V curves comparison where the I-V curve of the coil lies between the I-V curves of the tape measured at 40 mT and 60 mT perpendicular applied field. Also the critical current of the coil determined from the I-V curve, 66.4 A, is quite close to the $I_c$ values determined from the 40 and 60 mT perpendicular field I-V measurements, which are 65 A and 58 A, respectively.

This nice coincidence favours a little bit the hypothesis saying that the observed $I_c$ degradation in the coil is more due to the perpendicular magnetic field acting on the tape in the coil than due to the mechanical stress caused by winding the tape.

3.2. AC losses

Another type of experiment performed on both the coil and original Bi-2223 tape was the AC loss measurement. The superconducting sample (tape or coil) was carrying an AC transport current ($I_{\text{AC}} = I_{\text{ampl}} \cos(2\pi ft)$) and the voltage between the voltage taps was measured by a lock-in amplifier. From the first harmonic component of the voltage in phase with current the AC loss was evaluated. The frequency of AC current was $f = 21$ Hz in all measurements and they were performed in liquid nitrogen (77 K).

The results are shown in figure 5. Theoretical prediction of Norris for superconducting wire with an elliptical cross-section and critical current 140 A is also shown for comparison.

![Figure 5](image)

Figure 5. AC losses of the superconducting coil measured with directly connected and transformer coupled power supply compared to the losses of the original tape. Theoretical prediction of Norris’ elliptical strip model is also shown for comparison.

It is visible that the theoretical curve does not agree with the experimental data measured on the tape which are approximately 2 times higher. Further, the AC losses of the coil are approximately 10 times higher than those of the tape. This loss increase coincides with the results presented in [5] where a different kind of Bi-2223 tape was utilised.

AC loss measurements on the coil were performed in two different experimental set-ups. In the first one the AC power supply providing the AC current is coupled to the superconducting sample via a transformer and in the second one the power supply is directly connected to the sample. Simplified schematic drawings of these set-ups can be found in figure 6.

Transformer coupling of the power supply is most often used for AC loss measurements because it eliminates the problems with ground loops and common mode noise in the apparatus. However, we have decided to develop a measuring apparatus using also the directly connected power supply since we intend to use it for loss measurements with AC current superimposed on a
DC offset. We believe that such conditions could simulate the operation of a superconductor in a wind turbine generator and the power supply we are using allows to generate current waveforms of this kind.

It can be seen that the results of the AC loss measurements in both set-ups are in very good agreement. Due to the high impedance of the transformer’s primary winding we were not able to reach the same maximum current amplitude with the transformer coupled power supply. In the case of directly connected power supply we found necessary to measure the voltage difference between the two voltage contacts either by selecting a differential input of the lock-in amplifier or by using a differential pre-amplifier.

4. Conclusion
We have prepared a superconducting circular test coil wound from Bi-2223/Ag wire laminated with brass. The coil is self-supported, impregnated with epoxy fibreglass. It was tested in liquid nitrogen and the current-voltage curve and AC loss characteristic of the coil was measured and compared with the measurements on the original tape.

The I-V curve of the coil can be well fitted with the power law function with the parameters $I_c = 66.4 \, A$ and $n = 11.2$. Comparison with the I-V curves of the tape shows that it lies closest to the curves measured with 40 mT and 60 mT DC magnetic field applied perpendicular to the tape. This plausibly coincides with result of a simple electromagnetic calculation which estimates the maximum field at the coil’s winding to $\sim 60 \, mT$.

The AC losses of the coil are approximately 10 times higher than the losses of the original straight tape and we managed to measure them in two different experimental set-ups – with the transformer coupled and with directly connected power supply.

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