AC Application of Second Generation HTS Wire

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Abstract. For the production of Second Generation (2G) YBCO High Temperature Superconductor wire American Superconductor uses a wide-strip MOD-YBCO/RABiTS™ process, a low-cost approach for commercial manufacturing. It can be engineered with a high degree of flexibility to manufacture practical 2G conductors with architectures and properties tailored for specific applications and operating conditions. For ac applications conductor and coil design can be geared towards low hysteresis losses. For applications which experience high frequency ac fields, the stabilizer needs to be adjusted for low eddy current losses. For these applications a stainless-steel laminate is used. An example is a Low Pass Filter Inductor which was developed and built in this work.

1. Introduction
Second Generation (2G) High Temperature Superconductor wire, based on YBCO Coated Conductor technology, is gradually replacing the 1G HTS wire based on Bi-2223. The main reasons for this replacement are the anticipated reduced production cost for 2G HTS, while its in-field performance, especially at higher temperatures, is superior to that of Bi-2223. The scaling of the 2G HTS processing at various companies worldwide is making excellent progress, with American Superconductor (AMSC) installing a pilot operation with 720 km/yr gross capacity by the end of the 2007 [1].

In its production AMSC uses a bi-axially textured NiW substrate onto which a thin epitaxial oxide buffer layer is deposited (RABiTS™). The superconducting YBa₂Cu₃Oₓ (YBCO) layer, about 1 µm thick, is grown using a low-cost, solution-based Metal Organic Deposition (MOD) process [2]. The coating processes allow a wide (40 mm or wider) format. The process is also amenable to chemical modifications and doping to improve flux pinning and enhance in-field performance. After YBCO reaction and Ag coating the conductor is slit to multiple 4 mm superconductors. These “insert” superconductors are laminated on both sides to either copper or stainless steel. In this geometry, sold as “344 superconductors” and shown in cross-section in Fig. 1, the lamination provides mechanical, electrical and thermal stability and facilitates a winding process. I/cm-width is increased through the development of thicker YBCO layers and application of improved flux pinning [3,4], and performance levels are adequate for many commercial applications.

These 344 superconductors, having a single ~1 µm thick, 4 mm wide YBCO layer, are well-suited for DC applications but not directly for demanding ac applications. For these a special adaptation of the YBCO layer will most likely be needed, such as striation of as-deposited layers or direct inkjet printing of filaments which are converted to superconducting YBCO filaments. So far these technologies have only been demonstrated in short lengths. In addition, an effective filament transposition scheme would need to be developed [5]. For these reasons less demanding ac
applications which can use unstriated conductors are of direct interest in the near-term demonstration of HTS devices which use alternating transport currents. Examples are fault current limiters, MRI magnet systems, and, as discussed in this work, low pass filter inductors (so-called buck inductors).

AC loss in a non-striated 2G HTS wire has three components: eddy current loss, hysteretic loss, and, in case of a magnetic substrate, the ferromagnetic loss. The eddy current loss is less of a problem for 50-60 Hz applications even when using a copper stabilizer, at temperatures of 50 K and higher. For applications with a high frequency magnetic field component, the nature of the stabilizer is increasingly important. For the buck inductor in this work a 5 kHz component would induce unacceptable losses in a Cu stabilizer, and for this reason a stainless steel stabilizer was selected. The AMSC 2G HTS process does have this option as it uses a lamination process to apply the stabilizer. The stainless steel foil (0.025x4.3 mm 316) is also half the thickness of the standard Cu stabilizer, which further reduces the eddy current loss component. Figure 1 shows a cross-sectional representation of 344S superconductors.

In the past few years ac transport losses in 2G HTS have been extensively reported [6-13]. The nature of the YBCO film, being 1 µm thick and 4-10 mm wide and having an aspect ratio of 4x10^3 to 10^4:1 would suggest ac transport losses following the Norris strip model. However, in 2G HTS with a non-magnetic substrate the losses are higher and follow the Norris ellipse model closely [6]. Loss measurements and modeling of 2G HTS with a magnetic substrate see a further increase in transport losses, in particular at lower currents. Figure 2 shows an example for a 4 mm wide “insert” wire (a superconductor without laminate) based on a NiW substrate; the solid line shows an enhanced loss over the Norris Ellipse prediction (dotted curve).

The loss of the weakly ferromagnetic Ni-5at% W substrate has been measured by various groups [8-10]. And while the actual shape of the M-H curve is under discussion, the losses agree reasonably well. While they cannot be neglected, they are not very high. However, when the ferromagnetic loss is simply added to that of a Norris ellipse curve, the total loss curve underestimates the loss of the conductor [6,10]. Apparently a magnetic substrate has a second contribution to the loss, which comes from the enhanced field in the superconductor due to the enhanced permeability (µ_r=100 for NiW at 77 K). To complicate matters further, losses as measured for a single conductor are different from losses in conductors which see more than one substrate and which are often lower. In a double conductor lower loss was demonstrated, now following the Norris ellipse model [11]. Lastly (an important feature of the present work), the dependence of the transport losses on µ_r suggest that in a DC background field of sufficient strength to saturate the magnetism in the NiW, µ_r would be close to...
1 and hence lead to a practical reduction in total loss. This effect can also be observed in Figure 2, where application of a DC background field substantially reduces loss at lower amplitudes. Hysteretic loss measurements in 2G HTS wire with a NiW substrate, using various stacking modes, have demonstrated a significant difference between a single and a stacked conductor [12]. In particular, a double conductor with a face-to-face arrangement saw a significant reduction below the penetration field. Losses in small coils have been modeled for substrates with $\mu_r$ ranging from 1-100 [13,14], showing the potential for an enhanced loss due to the presence of a magnetic substrate.

2. Low Pass Filter Inductor (“buck inductor”).

In this project we want to demonstrate the use of 344 superconductors in an ac environment. A low pass filter inductor (“buck inductor”) was considered of practical interest. A copper version is commonly used, and a cryogenic version appeared to offer significant advantages in terms of weight. The copper version is a heavy gauge copper toroid operating at 156 A dc with a superimposed 5 kHz ripple of 6 A or less. This DC+AC operating condition was considered advantageous for the HTS version as it would offer the best option to saturate the NiW substrate and therefore reduce losses.

Desired inductance was in the range of 2-20 mH. Inductors with an inductance at the lower end would need the smallest amount of superconductor but would see the largest ac amplitude and losses, while an inductor with high inductance would need more superconductor but have the benefit of a lower ac amplitude. Initially the superconducting version was expected to run at 65 K but with the enhanced flux pinning being realized in the 344 superconductor it was decided to design the Inductor for use at 77 K. For the 5 kHz component a thin stainless steel laminate appeared well-suited.

The 156 A current level, at 77 K and parallel fields of ~0.4-0.8T, can be met in the near future using a two-in-hand winding, and a so-called double coat technology which has been demonstrated in R&D but has not yet been incorporated in the AMSC baseline process. For this reason we divided the Inductor demonstration into two phases:

Phase I: Standard 0.8 $\mu$m YBCO layer 344 conductor, operates at 70 A DC
Phase II: Double coat 1.4 $\mu$m YBCO layer 344 superconductor, operates at 156 A DC

Both Phases would see three Inductor coils. The Phase I is a learning phase, and hence the three inductors are made with the same amount of wire and coil geometries but using different construction methods. In this paper we report on the construction and testing of one of these Phase I Inductor coil. In the Phase II all three will be similar and will see final testing as a three-phase Inductor. For each three-coil inductor 770 m of superconductor is available, or 256 m for each of the three inductor coils.

2.1. Toroid versus solenoid configuration

For the Inductor coil a toroid configuration was compared to a solenoid configuration. Figure 3 shows the field profiles for the two configurations. In both cases 16 double pancakes (DPs) were assumed (32 single pancakes), connected in series, assuming a current of 80 A. In the toroid configuration on the left, all coils have the same field distribution, with a high parallel (to the wire’s tape plane) magnetic field near the inner toroid diameter. The perpendicular field component increases towards the outer section of the toroid but its strength, while not negligible, is low. The solenoid configuration on the right shows the field in one quarter of the solenoid (a section with 8 DPs, or 16 pancake coils). The top DP shows a strong perpendicular field component, with a field at 45° having a field strength of about 50% of the maximum field. For this reason the toroid configuration was chosen. The DP construction method is flexible and does allow later testing of the same DPs in a solenoid configuration.

2.2. DP construction

A common coil construction method for 1G HTS and 2G HTS coils is the co-winding with an insulating material (fiberglass, Kapton or paper) and vacuum impregnation with epoxy after winding.
In addition, various additional methods are used to ensure coil integrity. After vacuum impregnation the coils are robust but the epoxy does limit heat transfer to the LN$_2$. This was measured in a potted prototype pancake coil which self-quenched at around 1800 Hz, 10 A amplitude. Total dissipation at quench was around 8 W, or 1.8 W/m. Repeated quenching did not damage the coil or change the V-I curve. This measurement did not include a DC off-set current, and testing of a single pancake does create a strong perpendicular field component. The loss in such a coil when placed in a toroid configuration with a DC bias current was therefore expected to be much less.

The epoxy-impregnated (“potted”) coil construction method was selected for the first Inductor coil, Inductor coil 1A. In a second coil construction method, not reported here, coils are not potted, and the superconductors are separated by a medium which allows penetration by LN$_2$.

All coils were wound using a two-in-hand method, placing the two 344S superconductors in a face-to-face configuration. The pancake coils are connected to form a DP in the inner turns using a copper joint. Figure 4, left, shows a single DP coil mounted on a thin-walled G10 support tube. In the middle the toroid assembly is shown with 14 DPs in place.

The DPs are mounted on a G10 disc provided with threaded stainless support rods. On the right the completed toroid is shown. DPs are connected in series through the copper current leads, as shown in the center picture in Figure 4. The details of the Inductor coil are shown in Table 1.
Table 1. Inductor coil 1A characteristics (epoxy-impregnated)

| Description                                      | Value       |
|--------------------------------------------------|-------------|
| Number of Double Pancake coils (DPs)             | 16          |
| Number of windings per DP                        | 44          |
| Total Inductance at RT                           | 5.2 mH      |
| ID/OD pancake coils                              | 48/74 mm    |
| Toroid radius to center line                     | 64 mm       |
| Amount of 344S per DP/ per Inductor coil         | 16 m / 256 m|
| Critical current at 0.1 µV/cm                    | >50 A       |

3. Inductor 1A Characterization and Discussion

3.1. DC testing
All pancake coils were tested before and after assembly into a DP. The DP test showed that the internal joint had a very short region where only one of the two conductors was active. This limited the performance to around 50 A as assembled in the toroid (this joint problem was solved for Inductor 1B which will operate at higher DC currents). On average the pancake-pancake resistance was 3-4 µΩ. The DP-DP resistance was higher, being 350 µΩ total, or ~22 µΩ per DP-DP joint.

3.2. AC testing
We have obtained preliminary loss measurements for this toroidal Inductor 1A, as shown in Figure 5. It is convenient to evaluate the equivalent ac resistance, \( R_{ac} = \frac{P}{I_{rms}^2} \), where P is the loss in the coil and \( I_{rms} \) is the ac current. Fig. 5 shows that \( R_{ac} \) for an ac current of 2.7 A\( I_{rms} \) is linear in frequency. This would be expected for hysteretic superconductor loss as well as hysteretic ferromagnetic loss. As a dc current component is added, the loss drops, by a factor~4 for 20 A dc. A figure of merit for inductors is the quality factor \( Q = \frac{L\omega}{R} \); for a superconducting coil this is approximately independent of frequency. With a 20 A dc current we find \( Q \approx 400 \), an impressively large value.

With increasing dc current \( Q \) increases further. At higher dc currents the loss drops to a point that it cannot be measured accurately with our equipment. It is well known that Q's of this order are difficult to measure accurately, since extreme phase accuracy is required.

Figure 5. AC loss testing of Inductor 1A (toroid).
Equivalent resistance versus frequency.
2.7 AB\( I_{rms} \) .
DC bias current: 0, 10 and 20 A.
\( T = 77 \text{ K} \)
We can speculate that the loss with no dc current is dominated by ferromagnetic effects. In [13] it is shown that a permeability $\mu = 100 \mu_0$ in the substrate can theoretically increase the loss 3-fold. Then a dc current might be sufficient to magnetically saturate the substrate, which would reduce the ferromagnetic response to smaller ac fields. Another clue is that the inductance drops, by as much as 17%, with increasing dc current. This again could be a result of a reduced ferromagnetic contribution. Further analysis is required before the mechanism can be settled.

The loss in the inductor was also measured at an ac current of 5.5 A rms. The slope of $R_{ac}$ vs. frequency is nearly the same as for a current of 2.7 A rms. This implies that the loss is nearly proportional to (current)$^2$. This is definitely not expected for the superconducting loss in a coil, which should increase faster than (current)$^3$ [14]. This again suggests that the loss (with no dc current) may be dominated by ferromagnetic effects.

If the loss remained linear in frequency up to the desired operating value, 5 kHz, we would have total dissipation of the order 10 W at 5 A rms which is certainly manageable (assuming the value $Q=400$). In other smaller coils we have found a (frequency)$^2$ loss component which can dominate at 5 kHz (see Fig. 4). Its magnitude is too large to be explained by eddy current effects in the stabilizer if it is comprised of SS. This may be a heating effect. In any case, further work is required to determine how serious this effect is in the toroidal inductor.

4. Conclusions
A first demonstration was made of a 2G HTS low pass filter Inductor which operates at DC current and a 5 kHz AC current. A toroid configuration appeared beneficial in avoiding perpendicular field components and was selected over a solenoid configuration. A toroid with 16 double pancake coils was built, which used 256 m of 344S superconductors. The measured inductance at RT was 5.2 mH. Measurements at up to 400 Hz show a significant reduction of losses with DC bias current. A high quality factor of $Q=400$ could be realized. The presence of a weakly magnetic NiW substrate appeared less significant for losses in this particular device. The reason for loss reduction with DC current is most likely saturation of the NiW ($\mu \rightarrow 1$).

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