A Critical Review on AC Losses in first Generation and Hybrid HTS tapes

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ABSTRACT

Cooling strategies in SMES devices involved to sustain appropriate environment for high temperature superconductors are crucial for smooth operation of SMES devices. However, amount of cooling to be done depends upon heat generated inside the HTS tape which ultimately is proportional to AC loss generated . Research has been conducted for SMES devices and various aspects related to AC losses such as computational and numerical AC loss predictions, reviews on use of various numerical methods for AC loss estimations have been explored. The present work deals with the critical review related to AC loss estimation for various HTS tapes used in SMES devices. Moreover, novel issues for the better emergence and development of HTS tapes have also been addressed.

1 Introduction

The solenoid magnets of SMES devices contains superconducting wire/tapes wound on a metallic mandrel to form a single or double pancake coil. Based upon critical current carrying abilities and operational capability in higher magnetic fields, the superconducting tape is divided into two types - YBCO and BSCCO tapes.

However, superconducting tapes because of carrying transport current, suffers from AC losses which are inevitable[1].The performance of SMES devices, due to heat generated because of AC losses, is seriously affected. In the past, several researches have addressed the critical issue of AC losses and have published useful literature. In this regard, Xu et al. predicted AC losses for SMES magnets in the intricate parts [2]. Mukherjee et al. reviewed the design and development of HTS energy storage devices for power applications. The current global status of various energy storage devices such as small scale, medium and large scale devices was presented. Moreover, complete SMES technology involving types of coil, converters and control systems was also overviewed [3]. Grilli et al. described various losses associated with commercial superconducting tapes such as hysteresis loss, coupling losses, eddy current losses and ferromagnetic losses and reviewed various methods and techniques to estimate these losses in commercial superconducting applications such as wires, tapes and devices [4].Similarly, use of H formulation technique, which is applied to superconducting tapes to solve for magnetic fields and then AC losses, was reviewed by Shen et al [5]. Governing equations and their implementation on various geometries were discussed and the utility of H formulation to estimate AC loss in tapes, large scale

windings and cables were discussed. Likewise, AC loss estimation results for various commercial superconducting technologies such as wires, cables, fusion devices, accelerators, superconducting generators were reviewed in detail [6-8].

However, the literature still does not contain a review on analysis of AC losses for first generation HTS tapes and hybrid tapes specifically used tapes in solenoid SMES devices. Therefore, in the present work AC losses associated with YBCO tapes, wound in solenoid configuration are critically reviewed. The paper contains sections in which AC losses for YBCO and hybrid based solenoid windings and tapes are discussed. The issues that can assist in emergence of this technology, are also presented.

2 Experimental analysis of AC losses in YBCO based solenoid windings and tapes

Magnetic fields plays a crucial role in coils especially perpendicular and parallel magnetic fields which are described in terms of their orientation with respect to tape surface. **Friedman Alex et al.[9]** conducted experiments to study HTS coils of YBCO pancakes so as to measure V-I curves of coils with DC and AC perpendicular magnetic field. Moreover, AC losses were also measured by electric and calorimetric techniques and its AC loss characteristics were plotted. Wet winding technique was used to wound non insulated wire with tape surface applied with epoxy filled alumina particles. V-I curve for single pancake coil was measured by placing HTS coil in between two opposite wound copper coil generating perpendicular magnetic field. It was observed that when placed under DC field, critical current of the coil does not show substantial variation with respect to the magnetic field. However, as the number of pancakes increased, the radial field also increased thus effecting the critical current strongly.

Under AC fields, a noticeable voltage was observed much before DC critical current value and the value of this voltage was strongly effected by the frequency and amplitude of the field. Moreover, the critical current of the coil first increased with the frequency, reached the maximum value and then decreased at a particular value of AC magnetic field. Similarly AC losses measurements were also performed using electrical meters and calorimetric technique with and without cryogens. The results from these two measurement techniques showed good agreement. In addition to this, it was also reported that AC loss showed strong dependence on current value for single pancake with and without single pancake nearby and pancake from double pancake coil as shown in figure 16. Moreover, it was also reported for multi pancake coils by the authors that the sun of the AC loss for entire coil was equal to the sum of the AC loss for individual four pancake coil and sum of the AC loss in two double pancake coil. It was also revealed that the overall AC loss for middle two pancakes was greater than outer pancake coils, even though the outer pancake were experiencing higher magnetic fields as shown in figure 1.

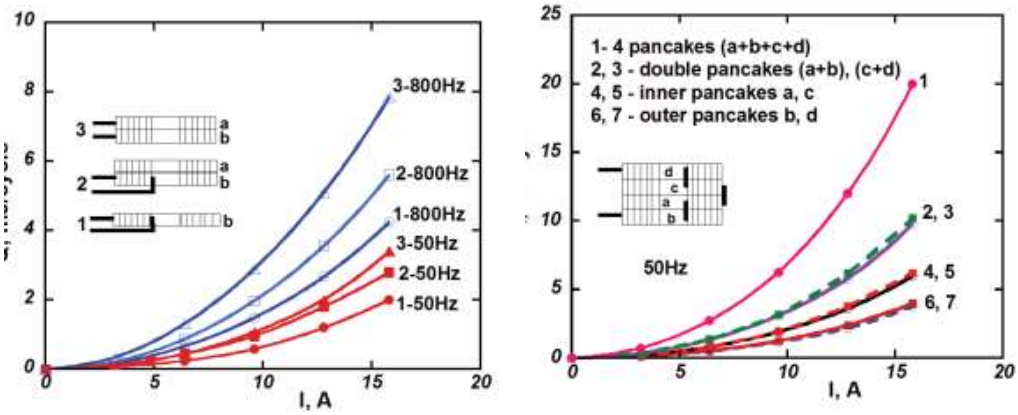

Figure 1 left showing AC loss variation with current at various frequencies for single pancake coil, right figure shows AC loss distribution in multi pancake coil [9]

Therefore I-V curves and AC loss measurements for YBCO coils were performed under perpendicular magnetic fields. However, the influence of parallel magnetic field should have been included to present a bigger picture.

In an effort to demonstrate the consequences of the surface inhomogeneities of the HTS tape, **Gomory et al.[10]** compared I-V characteristics of coil experimentally and computationally, made up of 12mm wide REBCO material having 10 turns. I-V characteristics suggested that calculated I-V predictions is more than that of the actual measured data of I-V. When the critical current in all the turns of the coil is assumed to be degraded by 2%, the obtained simulated results then matches the measured values of I-V.

Power dissipated in the coil due to contribution of from single turn is given by following expression (8)-

$$P = \sum_{i=1}^{N} \int_{S_i} J_s(r,z) E_{i,j}(r,z) dS \tag{8}$$

AC loss or the energy dissipated per unit length of the tape is (9)-

$$Q = \frac{\sum_{j=1}^{M} P_j \Delta t}{\sum_{i=1}^{N} 2\pi r_i} \tag{9}$$

AC losses in the coil were estimated and the results were compared with the experimental measurements and it was observed that sufficient agreement between two cases were possible when lateral non uniformity in the critical current density is considered. Electron microscope images were used and surface area of the tape without inhomogeneities was plotted against position with respect to the tape centre as shown in the figure 2**.** It was concluded that the tape suffered from lateral inhomogeneities at the edges of the tapes. In addition to this, AC losses in the tape was plotted against current for constant critical current and with certain degradations in the tape.

It was revealed that simulated AC loss with various constant I_c matched well with the experimental values. Similarly, critical current degradation of 7% and 25% in one turn did not produce visible changes in the AC loss values.

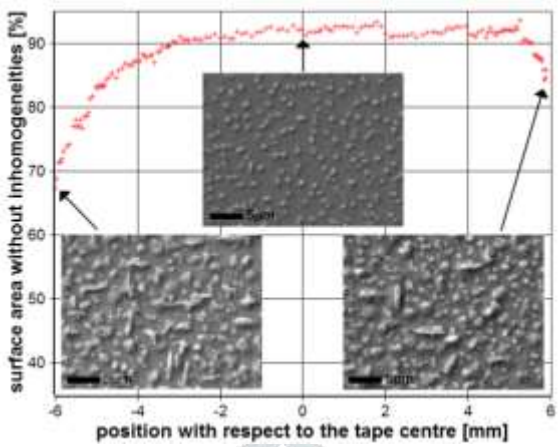

Figure 2 Electron microscope images at the edges of the tape [10]

AC loss distribution among the turns in the coil were analyzed computationally and coil with no degradation of critical current and coil with 75% degradation of I_c in first turn were selected. It was confirmed that for current value of 70A, AC losses values matched for higher turns but from inner most to turn number 4 , AC losses were different . 75% degradation in inner most turn of coil exhibit higher AC losses and the losses were transferred to the neighboring tapes i.e. upto 4th turn. However, at higher currents, higher AC losses were experienced along the turns of the coil. But the innermost turn had less AC loss value as compared to coil without critical current degradation as shown in figure 3

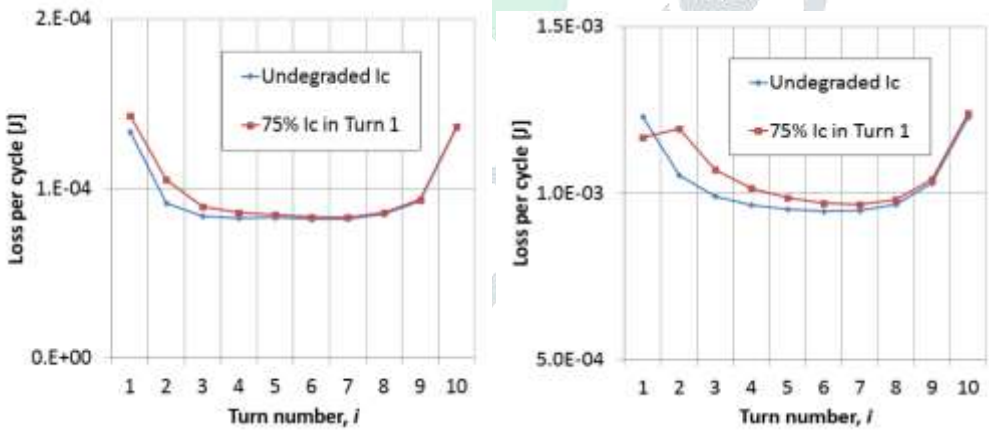

Figure 3 left graph at 70 A and right graph at 140 A [10]

The experimental validation of the surprising results is required in order to have a better understanding of the effect of AC current degradation on AC losses of the coil.

Roebel HTS Cable concept is a novel concept where the current carrying cable is divided into strands and each strand carries some portion of the total transport current. Also, the strands are transposed on each other along the length of the cable direction**. Kario et al. [11]** reported the DC and AC performance characteristics of HTS coils made up of Roebel Assembled Coated Conductor tapes by varying the

distance between the turns of the coil. Five different coils (C20, C10, C4, C1.4 and C0.1, where numbers denote distance between turns in mm) with five different space between the windings were prepared with styrofoam , paper and kapton as spacer material. The inner diameter of all coils were fixed i.e. 9.2 cm. However number of turns and outer diameter varied because of the space between turns varied. Table 1 shows the coil details used in the analysis.

Table 2 Coil Details

Coil	C20	C10	C4	C1.4	C0.1
Spacing (mm)	20	10	4	1.4	0.1
Spacing Material	Styrofoam	Styrofoam	Styrofoam	Paper	Kapton
No. of Turns	6	9	9	11	13
Outer Diameter (mm)	350	294	186	148	123

Under DC characterization, critical current of various coils and their corresponding power exponent n values were analyzed computationally and experimentally and were plotted as function of distance between turns in the coil. It was reported that coil having maximum distance between turns carried maximum critical current whereas coil having minimum turn distance, due to high magnetic field set up at the centre, had least critical current.

Similarly, under AC characterization, AC losses for the coils were studied and compared with straight conductors and Norris model cable with elliptical cross section. It was observed that the tightly wound coils had maximum AC loss as shown in figure 4.

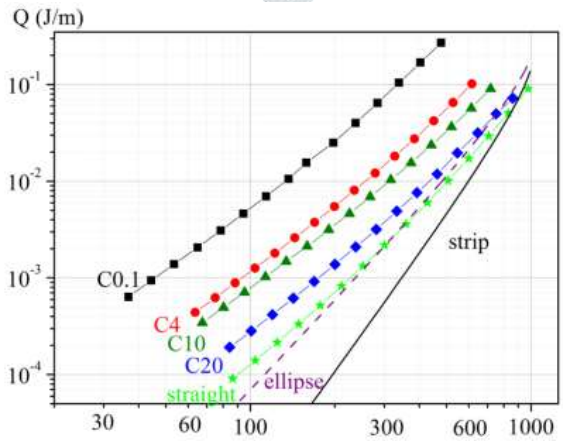

Figure 4 AC loss vs. current for various coils [11]

However AC losses for different coils showed less variation when the calculated magnetic field at the centre of the coil was used as independent parameter. In addition, when central magnetic field at the

centre of the coil was fixed to be 35mT, C20 coil showed maximum AC loss. It was due to injection of higher currents in the lesser number of turns of the coil to produce required amount of field intensity which resulted in high losses as shown in figure 5

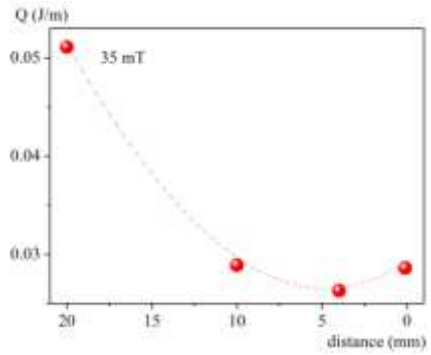

Figure 5 AC loss for coils with respect to space between turns of coil at fixed central field [11]

Therefore the present work could be extended to verify DC and AC characteristics of the coils having different shapes such as race track coil of HTS motors. Also the critical current dependency on magnetic field is not assumed in the analysis which plays a major role in estimating electric fields and then AC losses of HTS tapes.

3 Analysis of AC losses in Hybrid (containing YBCO & BSCCO) solenoid windings and tapes

Hybridization in solenoid coils is a another unique concept where cost and performance of coils are the deciding factors. **Jiang et al. [12]** measured AC losses and self field critical current for hybrid winding coil. at two temperatures of 77K and 65 K. The coil comprised of central windings REBCO wires whereas end windings are of BSCCO wires. REBCO wires have low self field critical current value and BSCCO wire have high self field critical current value. V-I characteristics of REBCO/BSCCO windings were measured at 65 K and 75K and were plotted for comparison with all REBCO and all BSCCO windings V-I characteristics.

Afterwards AC losses were also plotted against peak transport current at 65K and 77K. In addition, variation of AC losses and normalized AC losses were also studied at two frequencies i.e. 26.62 Hz and 43.96Hz. Moreover normalized AC loss values for hybrid coil at 77K was compared with the corresponding values of all REBCO and all BSCCO winding coils. For normalizing the AC loss value, $I_{c,assembly}^2$ was used whereas transport current was normalized by $I_{c,assembly}$. Measured experimental confirmed that AC losses for hybrid coil windings were less than all BSCCO winding coil but greater than all REBCO windings coil as shown in figure 6.

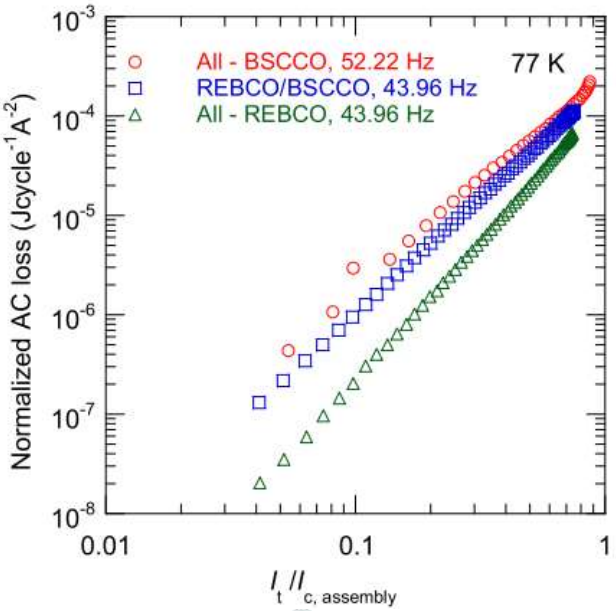

Figure 6 Normalized AC loss for various windings [12]

In order to design coils for various electrical applications, AC loss and manufacturing cost plays an crucial role. The results obtained above suggested that hybrid winding coil would be the optimized choice not in terms of AC loss only but also in terms of cost as well because REBCO windings are more costlier than BSCCO windings.

Wang et al. [13] investigated the validity of homogenized model of solenoid HTS hybrid coil containing YBCO and BSCCO magnets. The axis symmetric H formulation was applied to the model to obtain final Partial Differential Equation for solution of magnetic field. The actual model of the HTS coil contained top six and bottom six BSCCO double pancake coils and middle double pancake YBCO coils which are modeled by using homogenization technique as shown in figure 7.

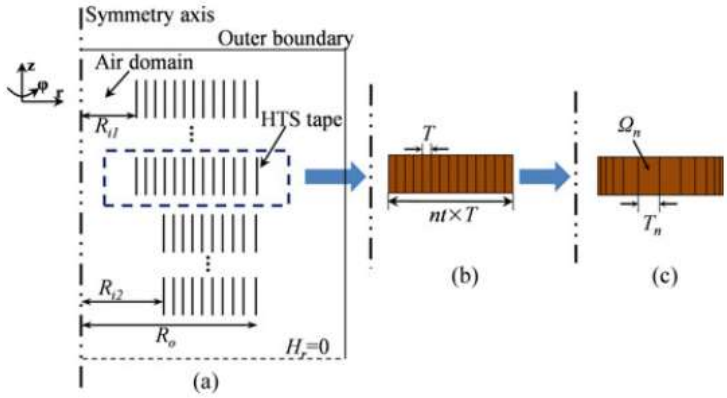

Figure 7 Actual half model of coil converted to homogenized form [13]

Afterwards, AC losses for homogenized model of YBCO & BSCCO coils were separately compared with the original model for two cycles of triangular current. It was concluded that homogenized modeling is best suited for YBCO coils as AC loss variation of homogenized YBCO coils matches in good agreement with original model of YBCO coils for two cycle of varying current (150 A- 300 A) as shown 8. The

same is not true for BSCCO coils because it was observed that AC loss variation for homogenized model of BSCCO coils shows good agreement with original model only for lower currents.

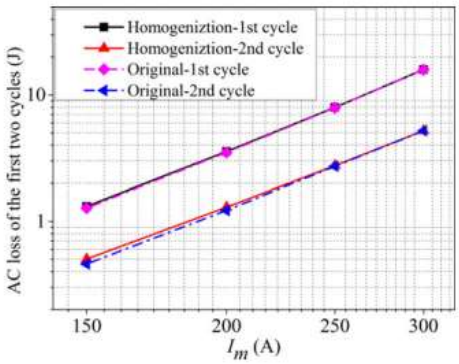

Figure 8 AC loss variation of homogenized YBCO coils with original models for two cycles of currents.[13]

Transport current of 162 A and dynamic current of 10 A with ramp rate 20A/s was used to measure AC loss for the entire coil. It was revealed by the authors that value of AC loss is maximum for first cycle of current i.e. 136 W. However, as the current cycles were increased, the value of AC loss start decreasing and is minimum for fourth cycle due to flux pinning effect as shown in figure 9.

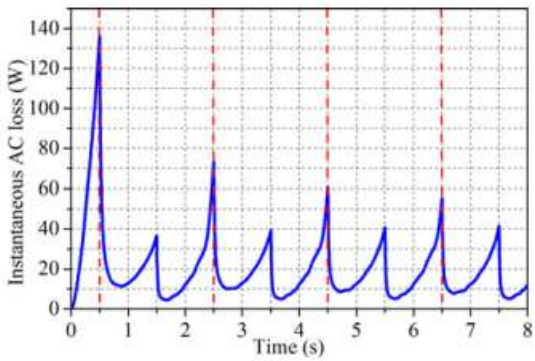

Figure 9 Instantaneous AC loss vs. time cycle [13]

Furthermore, the percentage distribution of AC loss at all the 18 pancake coils was also presented. It was concluded that the top four and bottom four ends of coil exhibited the major portion of total AC loss. In addition to this, it was also revealed that the steady state current, dynamic current and the ramp rate significantly effects the AC loss power.

Therefore it is suggested that more such hybrid magnets should be simulated and modeled with different arrangements of HTS coils so that these coils could be used as a better alternative of conventional HTS coil.

CONCLUSION

The present review article specifically addressed the issues of AC losses in solenoid high temperature superconducting (HTS) coil windings made up of 1st generation BSCCO tapes, 2nd generation YBCO tapes and hybrid coil windings containing both superconducting tapes. Although HTS coils constitutes useful technologies such as HTS transformer, HTS motor, Superconducting Fault Current Limiter (SFCL) but for the present review, only Superconducting Magnetic Energy Storage (SMES) based solenoid coils are considered.

It can also be confirmed that the AC losses either in YBCO or in BSCCO windings, depends upon magnetic flux angle and therefore only magnetic field distribution (and AC losses) should not be used as a deciding criteria for coil design. In addition, hybrid coil windings coils containing both YBCO and BSCCO tapes should be developed in order to create a balance between cost of the coils and AC losses.

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