A Review on AC Losses with BSCCO HTS tapes used in SMES Devices

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ABSTRACT

The performance of SMES devices are affected by various factors such as operating conditions of the unit, design of SMES, cooling strategies involved, thermo physical properties of High Temperature Superconducting material etc. Therefore, cooling strategies 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 .In the past research has been conducted for SMES devices and various aspects related to AC losses such as computational and numerical AC loss predictions and experimental AC loss measurement. The present work deals with the critical review related to AC loss estimation for BSCCO HTS tapes used in SMES devices.

1 Introduction

Superconducting Magnetic Energy Devices uses electromagnets, which suppresses power fluctuations in supply lines, are available in two designs - solenoid and toroidal [1]. Solenoid magnets can store higher energy for the same length of superconducting wire as compared to toroidal magnets. In addition to this, the solenoid magnets are less geometrically complex and hence the manufacturing cost of these are less in comparison with other magnets [2]. Therefore, due to simplicity in design and less manufacturing cost, in low and medium energy storage applications, solenoid magnets are preferred.

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, 1st generation tapes (BSCCO) and second generation tapes (YBCO).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. In this regard, Xu et al. predicted AC losses for SMES magnets in the intricate parts [4]. 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 [5]. 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 AC losses specifically for BSCCO tapes in solenoid SMES devices. Therefore, in the present work AC losses associated with BSCCO tapes, wound in solenoid configuration. Moreover, issues that can assist in emergence of this technology, are also presented.

2 AC losses in 1st Generation BSCCO based solenoid windings and tapes

Junfeng et al.[9] investigated AC losses and electromagnetic characteristics for Bi-2212 wire and coil by using H formulation with critical current density depending on magnetic field applied, in COMSOL Multi Physics software.The wire is represented as 37 ×18 configuration, means 18 strands and each strand contains 37 filaments. Hence a total of 666 filaments in one wire. In order to speed up the simulation and reduce the computational load, homogenization model is used where each strand is represented as one circle.

During simulation, external magnetic field parallel to the axis of the wire, ranging from 0.1T to 1 T with an increment of 0.1T was applied with Dirichlet boundary condition. The applied magnetic field is sinusoidal in nature with a frequency of 25 Hz. The transport sinusoidal current of peak value of 100 A was also provided to the computational domain. F**igure** 25 shows the Total loss and AC loss increases with increase in magnetic field.

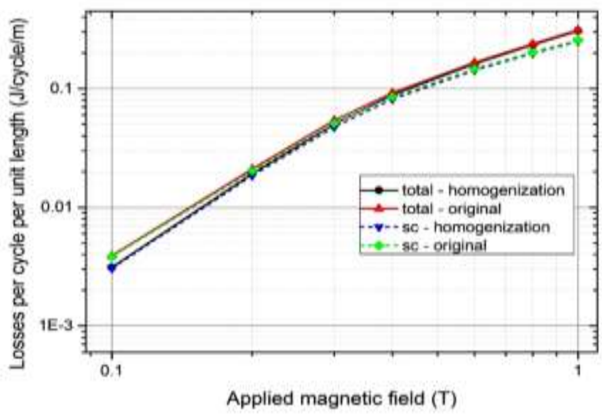

Figure 25 Total loss and Superconducting loss vs. magnetic field for original and homogenization model [9]

It can also be concluded that homogenized model is in full agreement with original model. In addition to this, variation of AC losses for wire was also investigated with respect to the surface roughness of the wire at various surface roughness levels. It was concluded that smooth surface had higher losses at lower fields but at higher fields, AC losses for smooth surface is maximum as compared to rough surfaces.

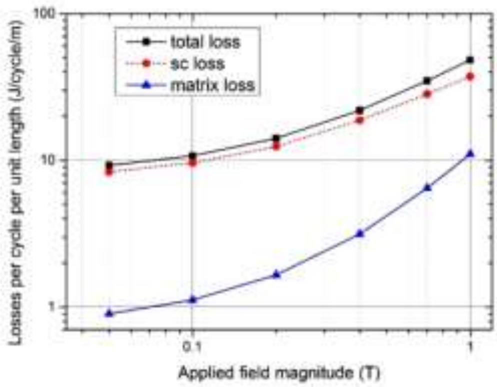

Figure 26 Losses vs. applied field for coil [9]

Figure 26 shows the variation of total loss, superconductor loss and the matrix loss for the coil with applied magnetic field. It can be observed that all losses increase with increase in the magnetic field. The present analysis had utilized circular Bi-2212 wires containing filaments. However, the analysis can be extended by using rectangular tapes instead of circular wires. Also the connections between filaments are not considered which if considered, can effect current sharing.

Safran et al.[10] performed experimental analysis for BSCCO tape based solenoid coil to investigate the effect of sheath material on AC loss which was measured by electromagnetic and calorimetric ways. Two single pancake coils with two different sheath material i.e. Stainless Steel (SS) and CA (Copper Alloy) were prepared and their critical currents were measured to be 93.4 A and 103.6 A. For AC loss measurement electromagnetically, three methods were adopted which are full coil method, contact loop measurement and contact less measurement.

Results confirmed that the AC losses for SS sheath material was found to be approximately equal to the corresponding values of CA material as shown in the **figure 27.** In addition, if the number of turns in a coil are increased, the values of AC losses also increases.

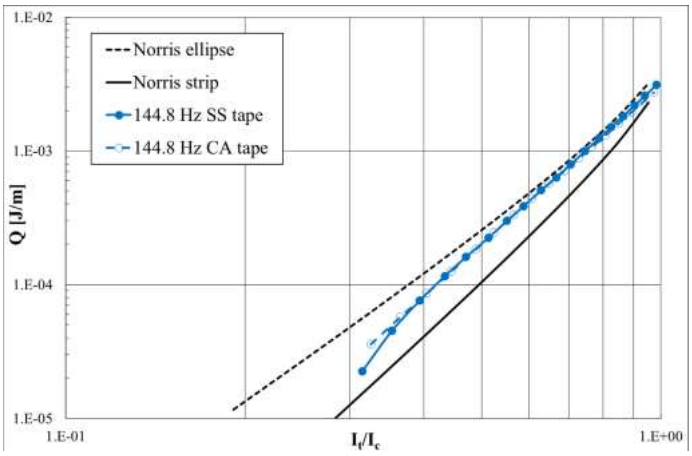

Figure 27 AC loss comparison between SS and CA tape and their validation [10]

The obtained results could prove to be extremely helpful in accessing AC losses for another configuration of solenoid coils. Moreover, experimental analysis can be extended to 2nd Generation YBCO tapes and logical results can be expected.

Numerical methods have always been utilized in the investigations of AC losses in HTS coils . **Amaro et al.[11]** performed a comprehensive experimental analysis on AC loss characteristics for HTS medium sized Bi-2223 coil at higher frequencies and compared the results with two different numerical methods which were Minimum Electro Magnetic Entropy Production (MEMEP) method and FLUX2D FEM based method. Frequency range of 72 to 1152 Hz was selected

Experimental results confirmed that AC losses increased with respect to current at various frequencies. However, the frequency dependent AC losses showed some unique pattern. The Value of AC losses decreased from 72 Hz to 144Hz and then increased till 1152Hz as shown in figure 28**.** The values of AC losses for certain frequencies were same but were showing a jump in the values after certain frequencies such as frequencies of 288 Hz and 864 Hz.

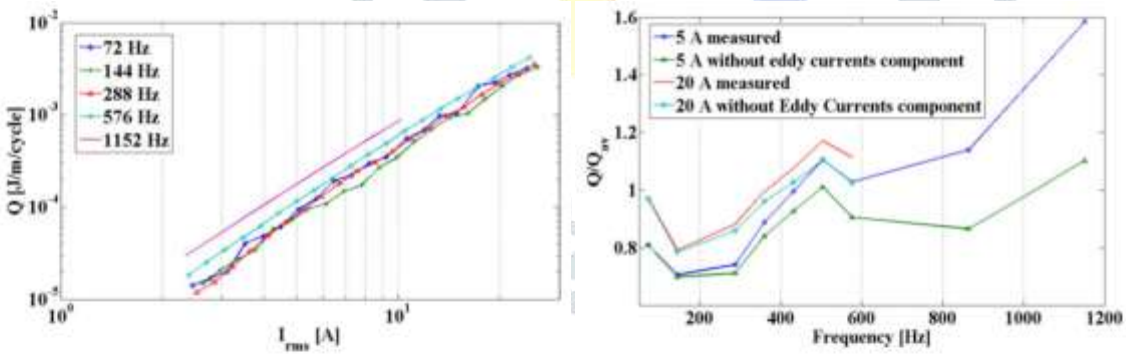

Figure 28 left shows AC loss vs. current at various frequencies, right shows Normalized AC loss vs. various frequencies at various currents [11]

Numerical method results of AC loss were also compared with the experimental results as shown in figure 29. It was confirmed that numerical methods proved to be effective in estimating AC losses.

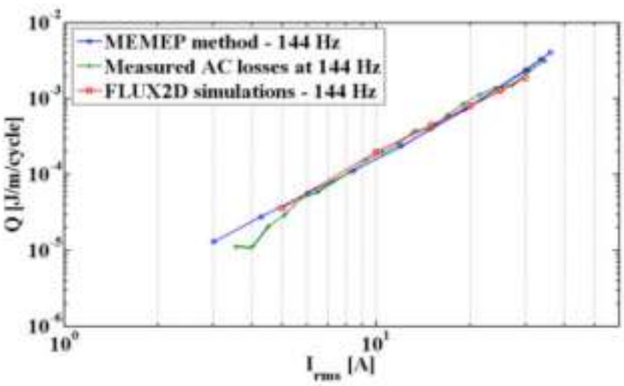

Figure 29 AC loss vs. Current by numerical and experimental techniques [11]

Therefore similar numerical and experimental analysis can be extended to measure AC losses for larger HTS coils in future.

Similarly, **Alex et al. [12]** experimentally studied AC losses for Bi-2223 single pancake, double pancake and multi pancake coils with different geometrical configurations and under various frequencies (20 Hz to 1600 Hz).

AC losses experienced by current carrying coil is maximum followed by the cases when there was spacer used and single pancake coil with no adjacent pancake coil as shown in figure 30. It was also observed that AC losses decreased with increase in the frequency level of the current.

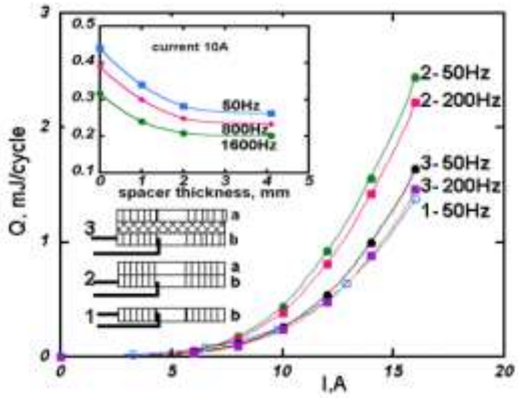

Figure 30 AC Loss for single current carrying pancake adjacent to another pancake in open circuit [12]

Moreover increasing the gap between single and double pancake coils, resulted in decrease in AC loss was also revealed.AC loss investigations of six pancake coils with and without air gap suggested that double pancake at the top of the coil without air gap experienced maximum AC loss whereas the bottom most double pancake coil in the coil having air gap had minimum AC loss. Even the AC losses for the single pancakes away from the gap in the six pancake coils with and without air gap, it was reported that the single pancakes away from gap without air gaps in the coil, had maximum AC loss as shown in figure 31.

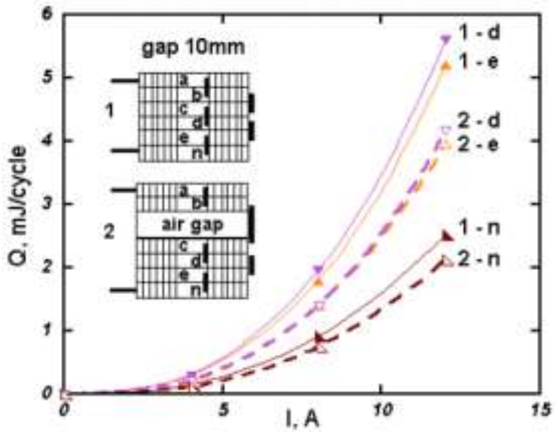

Figure 31 AC loss for single pancake coils away from gap in six pancake coil with and without air gap [12]

Therefore it was concluded that distribution of AC loss in coil is different from distribution in single wire. It was confirmed that losses in single and multi pancake coils strongly depend on adjacent open circuited pancakes and the distance between the pancakes. Hence magnetic field distribution and AC losses would never be the deciding factor in designing of the multi pancake coil. However, the effect of presence of double pancake coil on the current carrying double pancake coils is not included in the analysis.

Fukui et al.[13] investigated AC loss characteristics for Bi-2212/Ag tapes wound in a form of HTS coil. The estimated value of AC loss was compared with the measured AC losses which was investigated previously. The numerical formula for AC loss for the coil was formulated given by the equation (11). The current density distribution is estimated by solution of electromagnetic field equation containing magnetic vector potential and electrical scalar potential. The electric field inside the tape is represented by E-J power law shown in equation (12).

$$Q = \sum Q_{t,tape}(B_{sf,coil}(r,z), \theta(r,z)).2\pi r.S \quad (11)$$

$$E = E_0 \left(\frac{J}{J_C}\left(\left|B_{sf,coil}\right|, \theta\right) \right)^{n\left(\left|B_{sf,coil}\right|,\theta\right)} \quad (12)$$

In (11), $Q_{t,\ tape}$ is the total AC loss in tape at a particular location, $B_{sf,\ coil}$ is the magnetic field intensity and θ is the flux angle of the magnetic field with respect to tape surface at a particular position defined by r and z. The numerical analysis was performed by considering two coils having different turns with 20 single pancake coils stacked over one another. Coil A is wound with single tape without tension. Using this data, AC loss for the HTS tape was calculated and plotted against field angle at three external magnetic fields and varying transport current. One such plot is shown in the **figure 32.**

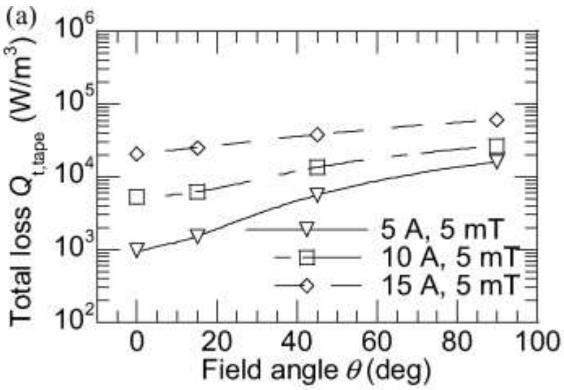

Figure 32 AC loss for tape vs. field angles for various currents at a fixed magnetic fields [13]

AC losses for the both coils were calculated and plotted against transport current. figure 33.

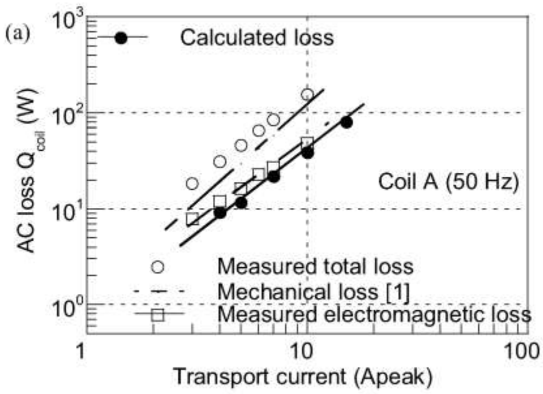

Figure 33 Calculated AC loss for the coil A vs. Transport current with measured total, mechanical and electromagnetic loss [13]

The AC loss density distribution profiles were also presented and it was concluded that value of AC losses is maximum at the edges of the coil.

Similarly, **Tonsho et al. [14]** developed an approximate method to calculate AC loss for HTS coil comprising 10 double pancake coils made up of Bi-2223/Ag tapes. AC loss formula for a coil was formulated in terms of AC loss for tape. For calculation of current density distribution in tape, electromagnetic field equation containing magnetic vector potential and electric scalar potential was considered given in the equation (13).

$$A_t = -E - \nabla V$$

$$j = -\frac{1}{\mu_0}.\nabla^2 A_s \quad (13)$$

Here A_t is magnetic vector potential, E is the electric field in the tape, j is the current density along the tape in z direction and A_s is the magnetic vector potential due to current in the tape. The magnetic field dependencies of critical current density and exponent n was presented in the graphs. The graphs showed measured critical currents and exponent n with DC external magnetic field at various flux angles. The measured data was validated with the predicted data from the previous work.

Therefore utilizing the above data, magnetic field distribution and flux angle distribution were also predicted as shown in figure 35

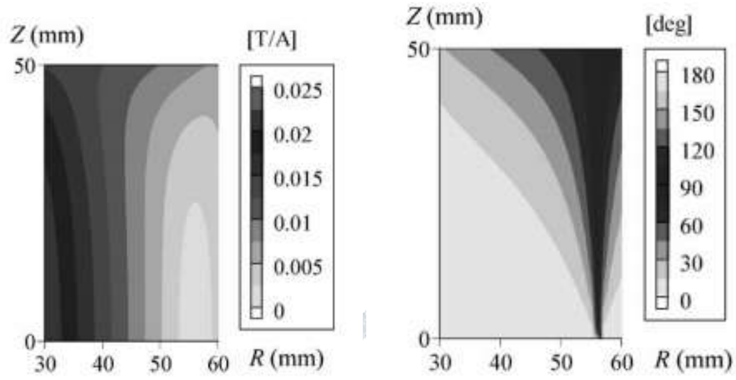

Figure 35 Left figure showing magnetic field in the coil and right showing flux angle distribution [14]

The AC loss in the coil was estimated using two values of transport current i.e. 12 A and 24 A. It showed higher losses towards the edge of the coil. Furthermore, using the above mentioned formulation, AC loss was calculated and was plotted against coil current. The estimated AC loss was compared with the measured AC loss of the coil before and after epoxy impregnation as shown in figure 36**.** It can be observed that the calculated values of AC losses were less as compared to AC loss values of the coil windings before and after epoxy impregnation. Hence the analysis could be extended to higher critical temperature tapes such as YBCO so that AC loss characteristics can be compared.

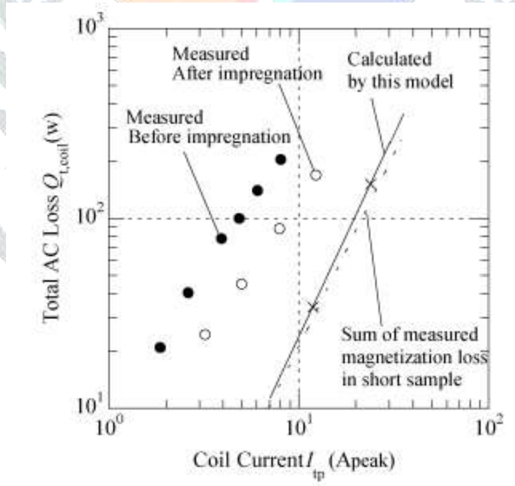

Figure 36 AC loss estimated and measured AC losses comparison [14]

The effect of carrying transport current by the HTS coil was analyzed by **Wolfbrandt et al. [15]** and the authors formulated AC loss mathematical expression for Bi-2223 rectangular tape wound in a single turn and experiencing parallel and perpendicular magnetic fields carrying with and without transport current. Eight coils were used to produce parallel and perpendicular magnetic fields, where four were producing parallel field and other four were producing perpendicular fields AC losses were measured by calorimetric technique, using AC currents and magnetic field, where temperatures of the tape were measured. The AC loss would result in Temperature increase which was measured by copper resistance wound along with the tape and thermocouples.

Hence AC loss was measured without transport current in tape and plotted against magnetic flux orientation at various values of magnetic field as shown in the figure 38. The data suggested that AC loss varied according to a formula (14)-

$$P = P_{\parallel} \cos^n \varphi + P_{\perp} \sin^n \varphi \qquad (14)$$

$P_{\parallel}$ and $P_{\perp}$ are the loss per unit length of the tape due to parallel and perpendicular magnetic fields respectively and the expression of these are already known. The parameters involved in these expressions were determined from measurements.

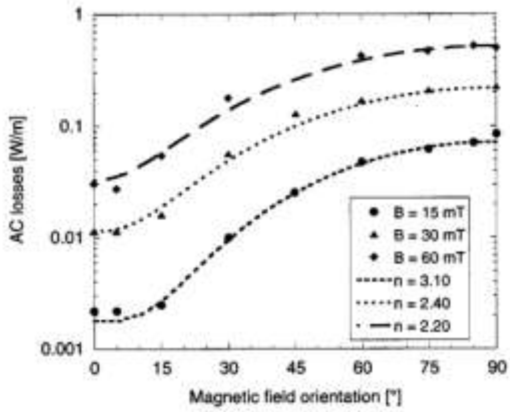

Figure 38 AC loss without transport current vs. magnetic field orientation (measured and fitted data) [15]

Likewise when AC losses are analyzed using transport current, a new ratio g (B, I, φ) was formulated- $g(B,I) = \frac{P(\varphi, B, I)}{P(\varphi, B, 0)}$. Two different magnetic field conditions i.e. 41mT and 100mT with different critical current densities were maintained and AC losses were measured and was plotted against magnetic field orientation as shown in figure 39.

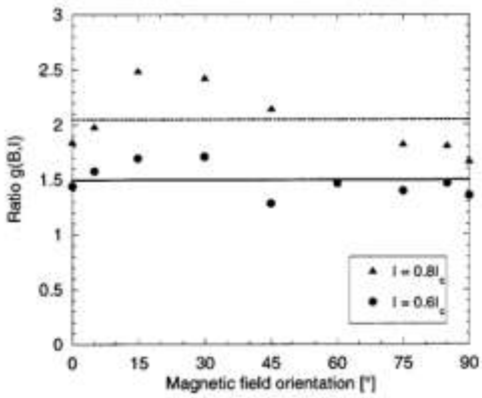

Figure 39 Ratio g vs. field orientation [15]

Therefore test results revealed that for currents less than 0.8 I_c, the ratio g did not depend upon φ. Hence the ratio g for the current case became (15)-

$$P(\varphi, B, I) = g(B, I) * P(\varphi, B, 0) \qquad (15)$$

It was found that the applied transport current and magnetic field used for the AC loss analysis were in phase with each other. Hence current and magnetic field applied could be used under out of phase condition to explore distinct results. Moreover authors have not explored transport current greater than critical current of the tape.

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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