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AC Loss Analysis on Coated Conductors at different Sinusoidal Frequencies for Electric Propulsion Applications

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Abstract. Superconducting magnets are one of the superior contenders in achieving the targets of electric aircraft industry successfully as they have very high power densities compared to other battery storage systems. Many aviation research agencies are looking at superconducting magnets as one of the alternate in replacing the conventional jet engines completely (electric aircrafts) or partially (hybrid aircrafts). National Aeronautics and Space Administration (NASA) and Air Force Research Laboratory (AFRL), USA has reported that high temperature superconducting magnets possesses higher specific energies (Wh/kg) and have infinite number of recharge cycles compared to other storage technologies employed for energy requirements. The other advantage of using such magnets is that there will be no hazardous disposals like batteries which lower the overall pollution. Superconducting magnets are DC operated systems however during charging or discharging transient behaviour of current results in the losses which would further ends up with heat generation. Heat generation during charging or discharging period would cause quenching of the superconductor due to sudden temperature rise.

In this work, electromagnetic analysis on superconducting magnet having capacity of 1 MJ has been performed where a 2D numerical model is developed using H-formulations in order to estimate the AC losses for a high temperature superconducting tape manufactured by SuperPower (SCS 12050) having 330 A critical current at 77 K. AC current having different load factors has been fed through the stacked tapes at 50 Hz, 60 Hz and 70 Hz frequency and AC losses have been evaluated. It has been found that at higher frequencies the AC losses are found to be larger than lower frequencies. Overcritical currents have been found in the current density distribution due to the application of E-J relationship for the homogeneous 2D numerical model.

1. Introduction

Electrical Aircrafts will be going to be the future of aviation industry as such aircrafts can deliver the expected outcomes without pollution compared to the conventional aviation transportation using jet fuels. Currently, a concept of hybrid aircrafts has been widely introduced by the aviation communities as they have to meet the pollution norms imposed by the parent governmental agencies. It includes the contribution of both conventional jet engines technology and novel electric aircraft systems where electrical power can be used during take-off, climbing and landing of the aircraft as it only contributes to 25% of the total power consumption [1]. For this to achieve, various battery operated systems have been evolved during past few years such as Lead acid, Nickel metal hydride batteries and Lithium ion batteries. However, these batteries have limited storage capacities per unit weight or surface area

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(Figure 1 (a) and Figure 1 (b)) and therefore for larger power requirement, the overall weight and surface area will increase which directly affects the lift force.

To conquer such challenges, a novel concept of using high temperature superconducting magnetic energy storage (HT-SMES) systems have been introduced by various research agencies like NASA [2] and Air Force Research Laboratory, USA [3]. The agencies have reported that for fully electric passenger aircrafts, one has to acquire SMES systems than battery storage units as they have higher power densities and capacities per unit weight and do not involve any hazardous disposal like chemical batteries. SMES system can provide more specific power (kW/kg) and specific energy (Wh/kg) (Figure 1 (a)) than supercapacitors, fuel cells, Nickel Hydride and Lithium ion batteries [3]. Air Force Research Laboratory, USA [3] has reported that SMES systems can store more energy per unit weight than other storage technologies (Figure 1 (b)). After noticing the importance of this concept, it has been identified that such systems can be useful for hybrid or fully electrical aircraft industry as they can provide efficient flight with lower risk as no moving part is involved in the design of SMES.

Usually, SMES is a DC operated device that store energy in magnetic field induced due to the flow of current through the superconducting tapes. However, during the charging or discharging period, the current needs time to achieve a study state thus implies current has to go through transient phase for few milliseconds or more depending upon the inductance of the coil [4]–[7]. This transient state is responsible for the AC losses among the pancake coils [4]. It has been well understood that self-fields can also affect the critical current of the tape [8] as well as AC losses among such coils. Also, in our earlier publication, it has been found that AC losses can be controlled by increasing the substrate layer thickness however overall flux density is found to decrease [9]. In the present study, a comprehensive analysis on HT-SMES has been performed at 77 K where magnetic field and current density distribution along with AC losses (W/m) have been examined. An alternating current having magnitude 200 A has been transported through HTS tape manufactured by SuperPower [10] at a frequency of 50 Hz. COMSOL MultiPhysics software package has been used to achieve the simulations where H-formulations model has been incorporated for the analysis.

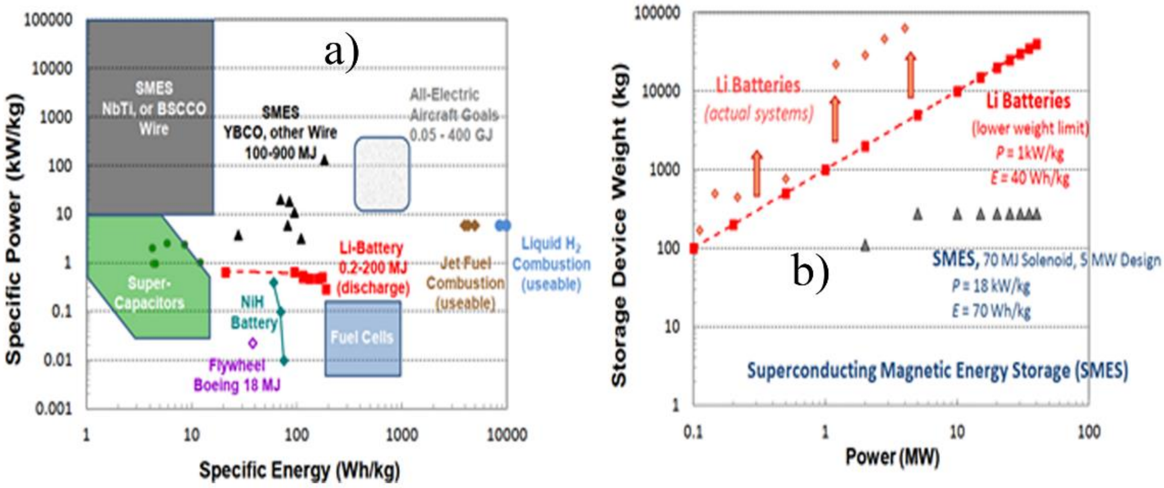

Figure 1. (a) Specific Power Vs Specific Energy, (b) Storage device weight Vs Power comparison for various Energy storage systems [3]

2. Electromagnetic Modelling of the HT-SMES

2.1. H-formulations

A similar formulation has been adopted as used by Brambilla et al. [11] and H-formulation has been selected as it is easy to implement and simple in operation. The governing equations involved in the electromagnetic modelling of the SMES are as follows [12]:

$$\nabla \times \rho \nabla \times H = -\mu \frac{\partial H}{\partial t}$$ inside domain Equation 1

$$H = H_{self} + H_{ext}$$ on boundaries Equation 2

$$\rho_{HTS} = \frac{E_c}{J_c}\left|\frac{J}{J_c}\right|^{n-1}$$ Equation 3

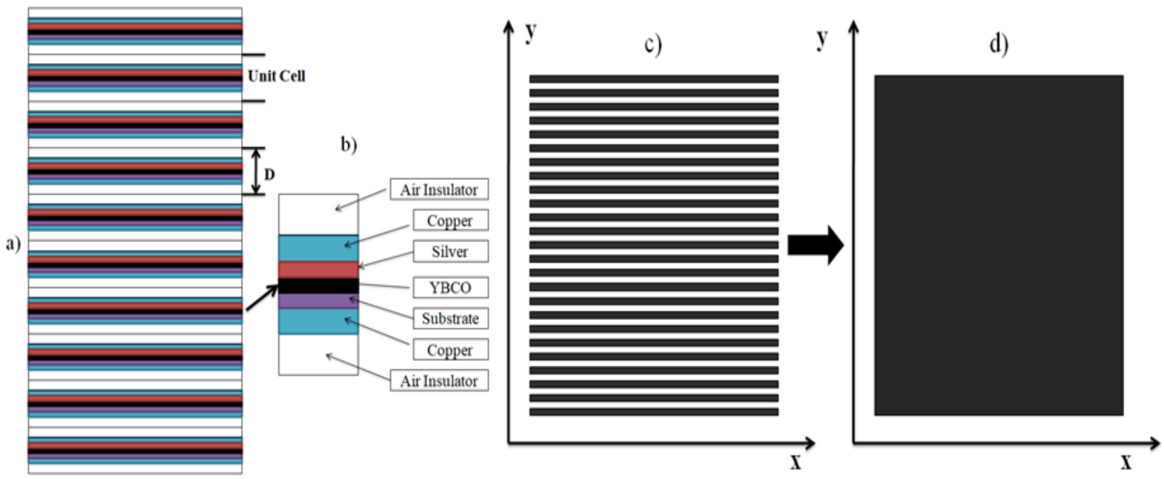

Figure 2. (a) Stacked coated conductors periodic arrangement, (b) zoomed section of unit cell, (c) stacked tapes representing turns around the coil, and (d) homogenized computational domain for the analysis.

Figure 2 shows the stacked tape periodic arrangement and homogenized domain respectively. In order to estimate magnetic field H inside the domain Equation 1 has been used along with the boundary condition imposed as Equation 2. Values for J, E and B can be calculated from H by making use of Ampere's Law $J = \nabla \times H$ and the following constitutive relations $E = \rho J$ and $B = \mu H$ respectively. The resistivity of the HTS tape can be modelled by incorporating Power Law (Equation 3).
Instantaneous AC losses (W/m) can be estimated using following relation (Equation 4):

$$\xi = \int_{Inside\,domain} E.J\,dxdy$$ Equation 4

A Kim like model (Equation 5) for the J_c (***B***) dependence of HTS tape at 77K was incorporated where B_0=0.04265T, Jc (77K,SF)=2.75×10^{10} A/m^2, k=0.29515, α=0.7 and B_{II}, $B_\perp$ are, respectively, the parallel and perpendicular components of magnetic field density with respect to tape's surface [12].

$$J_c(B) = \frac{J_c(77K,SF)}{\left(1+\frac{\sqrt{k^2|B_{\parallel}|^2+|B_\perp|^2}}{B_0}\right)^{\alpha}}$$ Equation 5

3. Electromagnetic Design of Superconducting Coil and AC Losses

Electromagnetic analysis for 1 MJ SMES is done using COMSOL MultiPhysics software where 2D model has been used to evaluate AC losses occur in HTS tape due to variable frequencies (50 Hz, 60 Hz and 70 Hz) and operating currents (200 A, 225 A, 250 A, 275 A and 300 A). The design parameters of 1 MJ SMES are available in Table 1. 2D analysis is done where 60 turns around a single pancake coil has been considered and through homogenized approach, the problem is solved using H-formulations.

4. Results and Discussions

4.1. Losses due to frequency change

AC losses have been calculated for the 2D numerical model using H-formulations. Figure 3 shows the instantaneous losses and Figure 4 shows the average AC losses (W/m) for the stacked superconducting tapes. It can be noticed that at higher frequencies, the losses get increased (Figure 3 (a)) and the losses variation is somewhat linear with frequency.

4.2. Losses due to current

AC losses have been computed using Eq. 4 where Figure 3 (b) shows the Instantaneous AC losses for different operating currents. It can be observed that the AC losses are found to higher at higher currents. It is also worth noting that the rate of increase in AC loss is found to higher at higher operating currents (275 A to 300 A) than at lower currents (200 A to 225 A). Figure 4 (b) shows the average loss variations with operating currents and the variation has been found exponential after fitting the data whose constants are tabulated in Table 2 along with standard errors, where I_{op} is the operating current. This exponential function can be used to estimate the AC losses among the operating current varying from 200 A to 300 A. Average AC loss of 368 W/m is found for 300 A operating current which is near to the critical value (330 A) and 80 W/m is for 200 A. This implies that AC losses are very sensitive to operating currents and found to increase with faster rates as operating current approaches to critical value.

Table 1. Design parameters for the HT-SMES

Description	Value
Stored Energy	1MJ
Bore Diameter	780mm
Coil Inductance	1.43 H
Cu cover height (each side)	20e-6m
Air gap and insulator height	2e-4m
Ag cover height	4e-6m
Substrate height	55e-6m
HTS layer height	1e-6m
Tape height	1e-4m
Tape width	12e-3m
Number of tapes	60
Coil height	0.018m
Resistivity of Air	1 m*V/A
Resistivity of Ag	2.7e-9 m*V/A
Resistivity of Cu	1.97e-9 m*V/A
Resistivity of substrate	1.25e-9 m*V/A
Frequency of transport current	50Hz

Table 2. Curve Fitting Parameters

Average AC Loss= exp(a+ b*I_{op}+ c*I_{op}^2)		
Constants	**Values**	**Standard Error**
a	1.55471	0.7187
b	0.01387	0.00551
c	2.10E-06	1.05E-05

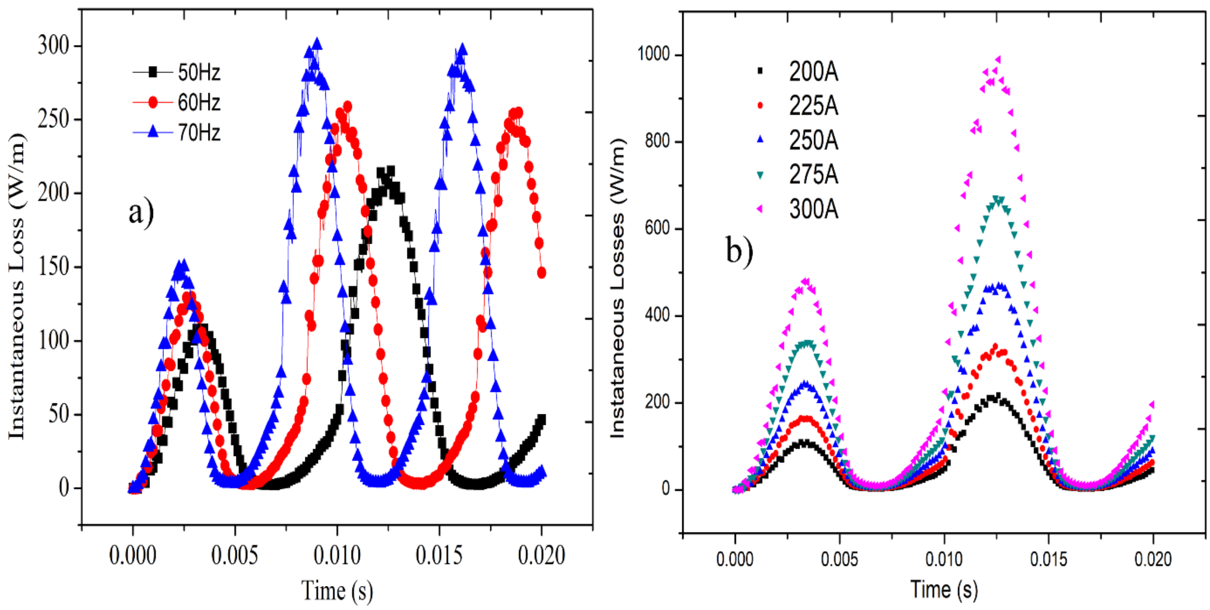

Figure 3. Instantaneous Losses variation with (a) frequency and (b) current

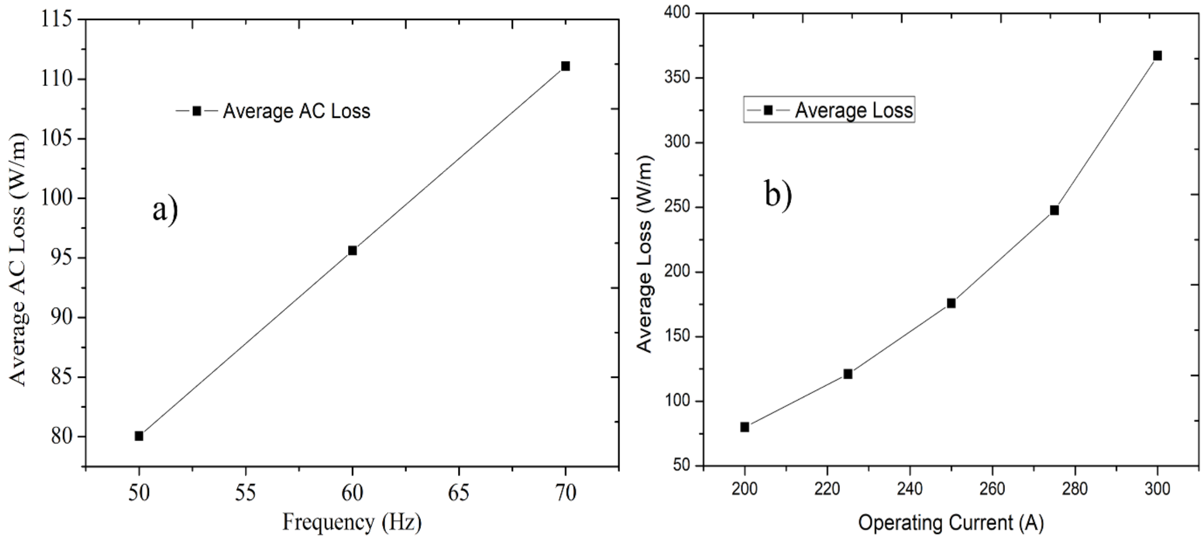

Figure 4. Average AC Losses variation with (a) frequency and (b) current.

5. Conclusions

For a current of 200 A and 60 turns on a single pancake coil, instantaneous losses are found to increase with frequency and the average losses are varying linearly with the frequency, however, the instantaneous losses are found to increase with increase in operating current and the rate at which these losses are increasing is more near the critical current. The average losses for different operating currents are increasing exponentially compared to the variation due to frequency change. So, it is beneficial if current should reach its steady state slowly means charging duration must be longer.

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