A Critical Review on AC Losses associated with YBCO based solenoid windings and HTS tapes utilized in SMES Devices

Gaurav Vyas

School of Mechanical Engineering, Lovely Professional University, Phagwara, 144411, India

ABSTRACT

Superconducting Magnetic Energy Storage (SMES) devices are nowadays become an integral part of modern smart grids. However, 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 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 .In the recent past a lot of research has been conducted for SMES devices and various aspects related to AC losses such as computational and numerical AC loss predictions, experimental AC loss measurement, 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 YBCO based solenoid windings and HTS tapes used in SMES devices. Moreover, novel issues for the better emergence and development of HTS tapes have also been addressed.

1 Introduction

Superconducting Magnetic Energy Devices uses electromagnets which suppresses power fluctuations in supply lines and hence are a vital component of any SMES device. These are available in to 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 as shown in figure 1.

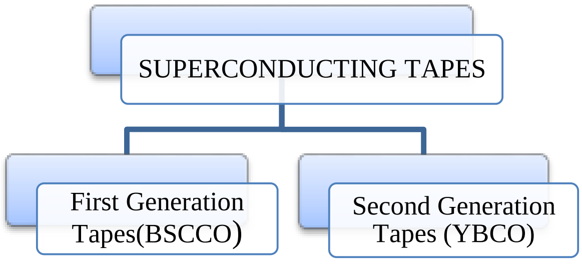

Figure 1- Types of superconducting tapes

However, superconducting tapes because of carrying transport current, suffers from AC losses which are inevitable[3].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 [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 AC losses specifically for extensively used tapes in solenoid SMES devices. Therefore, in the present work AC losses associated with YBCO tapes, wound in solenoid configuration and tapes kept in different operating conditions are critically reviewed. Moreover, issues that can assist in emergence of this technology, are also presented.

2 AC losses in 2nd Generation YBCO based solenoid windings and tapes

Wang et al.[9] employed a multi scale model to estimate current density, magnetic field and AC losses for YBCO based solenoid coil on large scale. Solenoid coil made of YBCO with six pancakes having 100 turns each was used for the analysis. In order to predict AC loss for entire tape, single tape was assumed to be located at various positions along the tape and AC loss at all those particular positions are simulated.

Figure 2 shows the simulated values of AC losses for three pancakes coils using three different models i.e. J infinite turn model, J uniform model and reference model at various values of currents selected . It can be observed that values of AC losses for J infinite turn model matches the values obtained for reference models more closely as compared to J uniform model. It can also be concluded that AC losses increase with the change of pancake coil. It is maximum for pancake number 3 which is at the bottom for all three values of currents.

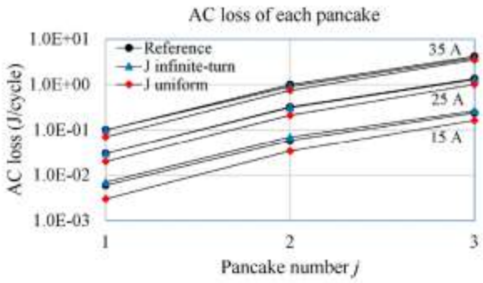

Figure 2 AC loss for each pancake using various models [9]

Multi scale model can be applied in two ways as demonstrated by **Zhang et al [10].** Authors estimated AC loss for solenoid HTS coil having four double pancake coils made up of YBCO tapes by four different techniques and compared those techniques in terms of computational speed and accuracy. Different techniques utilized distinct models which were Original reference model of the coil, homogenized model and multi scale models. Under multi scale model, J uniform model and model using Iteration method were simulated. The analysis was performed using commercial FEM software COMSOL Multi Physics. The AC loss was estimated using equation (3)

$$P = \sum_{i=1}^{400} \int_0^{2\pi} d\varphi \left(\int_{\Omega_i} r_i E.Jdrdz \right) \tag{3}$$

The computational procedure was conducted for three different transport currents i.e. 13 A ,17A and 21 A. The results suggested that iteration method improved the accuracy level of multi scale models with satisfactory computational speed. J uniform method is computationally faster but struggles as far as accuracy was concerned. It was also observed that the results of multi scale models were in good agreement with the reference model at the trough of the AC loss curve as shown in the figure 3. In addition, iteration methods results were matching up with the homogenized method results in terms of speed and accuracy in AC loss peak calculations.

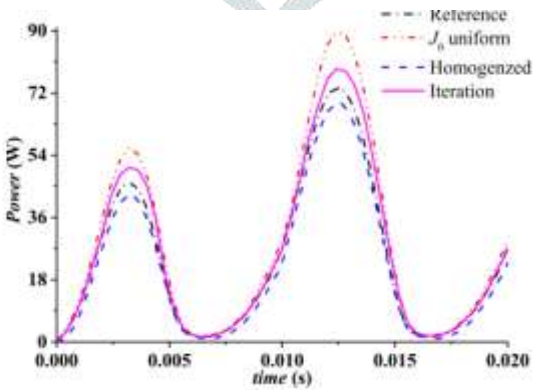

Figure 3 AC loss comparison for transport current 17 A.[10]

The accuracy of the analysis can be improved to further extent if higher order elements are used to model tapes while estimating current distribution along the sampled tapes. However, the computational speed will be compromised using higher order elements for all the models.

Similarly, **Peng et al.[11]** also designed solenoid type coil of 10MJ/5MW for SMES using homogenization model due to larger aspect ratio involved in the SMES coil. Initially the structure of the SMES was designed by genetic optimization technique and structural parameters were decided. Then the coils of SMES are connected in parallel configuration to increase current and reduce voltage among those. Then AC loss estimations were carried out by H formulation in COMSOL Multi Physics software.

Homogenization model reduced the degree of freedom and increased the accuracy. A two dimension axis symmetrical model of magnet was build and proper boundary conditions were set across air domain surrounding coil which was H_r=0 , where H_r is the intensity of vertical magnetic field. The model was simulated and the results of AC losses were shown in the form of AC loss ratio for double pancakes with respect to overall total AC loss.

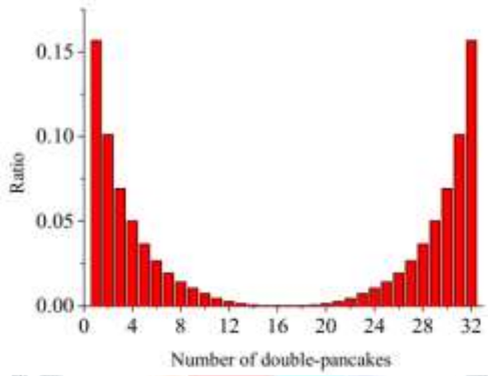

Figure 4 AC loss ratio vs. number of double pancakes of SMES coil [11]

It can be concluded from the figure 6 that for first four double pancakes of the SMES coil from both ends accounts for 51.5 % of the total AC loss. Similarly it is also observed that if first eight double pancakes are included, AC losses are 71.4 % of the total AC losses. Therefore the cooling strategies would be designed keeping in mind the results of AC loss obtained.

The present analysis was done for YBCO tape having width of 4mm and thickness of 0.5mm which could be further done for other strips having different dimensions. By these efforts, a clear picture of AC losses for different strips will be presented and the information could be extremely helpful for end users.

Zermano et al.[12] estimated AC loss for stacks and coil using homogenization model and original model. YBCO based superconducting stack was simulated using COMSOL Multi Physics software. For the analysis, two cases are assumed, one of transport current and another of applied magnetic field. For homogenized model, stacks of 16, 32 and 64 tapes were selected. In the first case of simulation with transport current, the aforementioned tapes were simulated with current value of 70 A, 60A, and 50A for vertical stacks of 16, 32 and 64 tapes respectively. The frequency of the current was 50 Hz. In the second case of simulation with applied magnetic field, amplitudes of sinusoidal magnetic field was 90mT, 100mT and 110mT for stacks with 16, 32 and 64 tapes respectively. The frequency of the magnetic field was 50 Hz. Meshing was performed using structured meshes for original stacks. For homogenized model, rectangular structured mesh along with triangular mesh for air domain was assumed.

Electromagnetic characteristics including normalized current density and magnetic field density for 32 tapes stack were presented and the results proved an excellent agreement between original model and homogenized model. In addition to this AC losses for both the models were investigated and it was concluded that both models are in full agreement with each other as shown in figure 5.

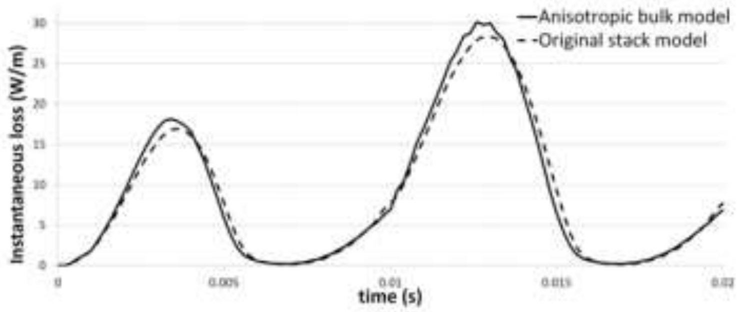

Figure 5 AC losses for homogenized model and original stack mode[12]

Alternating current sometimes carries distortions or disturbances. Therefore**, Asrami et al. [13]** investigated AC loss with current carrying harmonics for three different coils i.e. Single pancake, Double pancake and solenoid coils having five turns each.The coils were simulated using H formulation module of COMSOL Multi physics software. Figure 6 shows AC loss variation of solenoid coil simulating under 3rd and 5th Harmonics for different fundamental currents.

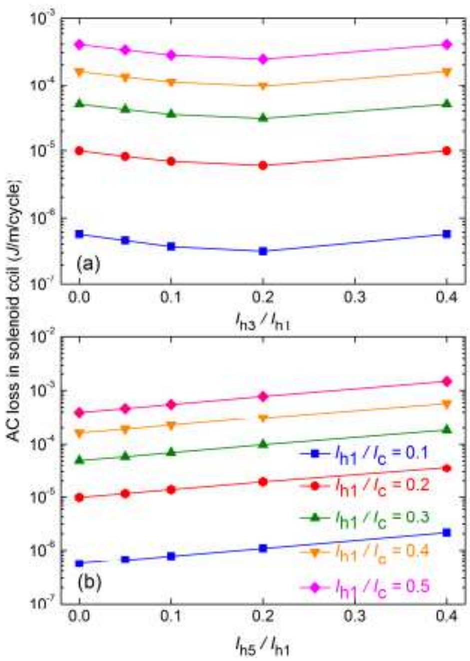

Figure 6 Variation of AC loss in solenoid coils under 3rd and 5th harmonics for different fundamental currents [13]

Therefore in this analysis, harmonics play a vital role as AC loss information for the present two harmonics will help in efficient designing of SMES coils. The analysis could be further extended for higher harmonics in order to access the AC loss information.

Zheng et al.[14] designed solenoid magnets for 10kJ SMES and investigated AC losses associated with it. Using the fundamentals of Genetic Algorithm, structural and magnetic field parameters was optimized. Under this, various variables, constraints and objective function were formulated and flow charts were developed for optimizing HTS coils. Then using genetic algorithm, energy storage requirements such as length of wire used etc. are optimized. Based upon the optimized parameters, dimensions and other parameters were selected for design requirements of SMES. Afterwards, mechanical stresses and structural parameters such as radial stresses , parallel magnetic field etc were investigated and design process of solenoid coil was completed.

However the design procedure of SMES coils is incomplete without AC loss evaluation of the coil during power exchange process. Hence for this purpose, modular design grouping of four solenoid magnets was done to reduce the inductance of each solenoid magnet coil thereby decreasing the voltage across both ends of the magnets. The operating condition of the designed SMES demands 6KJ of energy with dispersion rate of 4.5kW and 1.5kW as there are two energy release points in the system.

For AC loss evaluation, H formulation was used and to accelerate the computation, homogenization method was adopted. The AC loss curve obtained during discharge process is presented in figure7

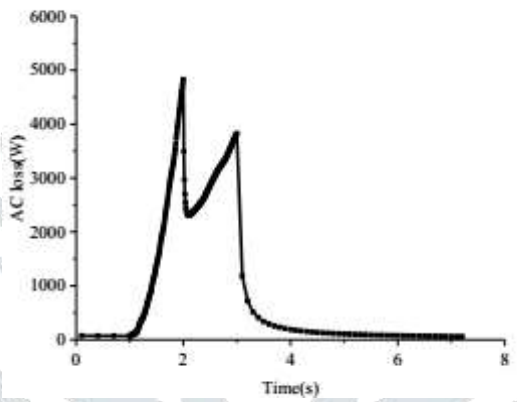

Figure 7 AC Loss for four solenoid magnet [14]

The AC loss distribution for SMES magnets is also presented and it was confirmed by the authors that the four double cakes at the end would account for 74.3 % of the total AC loss whereas if six double cakes coils at the ends were considered, it would result in 88.2% of the total AC loss. Therefore the information provided could be further utilized for designing the cooling strategies of the coil.In this regard, the working temperature of the magnets were 20K. The whole analysis would fetch different results by varying the temperature of the magnets. Therefore temperature effects should be included in the analysis.

Hong et al. [15] proposed a numerical method which involves solution of partial differential equations under H formulation in FEM based software COMSOL to investigate electromagnetic behavior of superconductors in uniform magnetic field, non uniform magnetic field and superconductor cable carrying transport current. Current density distribution and magnetic flux lines were drawn for the mentioned cases. If critical current density was field dependent, then (6)-

$$J_C(B) = \frac{J_{c0}.B_0}{B_0 + B} \quad (6)$$

Furthermore, AC loss for the superconducting cable carrying current was analyzed. In this regard, the variation of normalized AC loss was plotted against normalized transport current as shown in figure 8**.** The results proved a satisfactory match with model proposed by Norris.

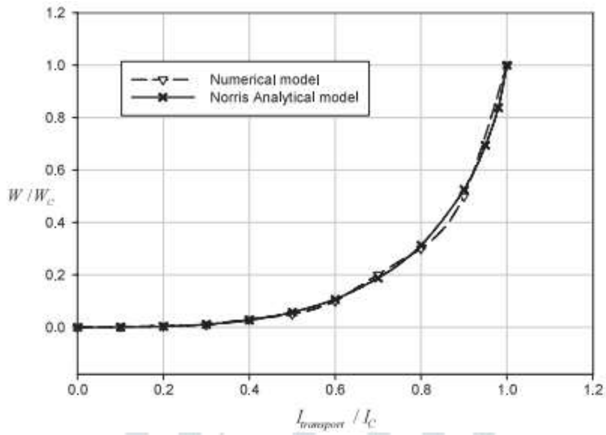

Figure 8 Normalized AC loss vs. Normalized Transport current [15]

Hence the numerical model was in good agreement with the already available analytical model. However, the model possessed enough potential to be extended to 3D analysis. In addition, various critical current models depending upon external magnetic fields can be utilized to validate AC losses.

CONCLUSION

The present review article specifically addressed the issues of AC losses in solenoid high temperature superconducting (HTS) coil windings made up 2nd generation YBCO 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 is observed that for AC losses in YBCO 2nd generation tapes wound in solenoid geometry with single pancake and double pancake configuration, various numerical models such as homogenization models, multi scale models etc. are used, to computationally estimate AC losses in YBCO windings. H-formulation technique is extensively used for computational models which can be solved in commercial FEM software nowadays. It can be concluded that during numerical estimation of AC losses for the extensively used 4mm wide YBCO tape or windings, substrate layers should also be included in the analysis. Moreover, usage of higher order elements and several critical current state models should be encouraged. In addition, the literature needs more experimental and numerical investigations of YBCO tapes with different dimensions.

REFERENCES

[1] S.M. Schoenung, W.R. Meier, W.J. Schafer," Associates comparison of large-scale toroidal and solenoidal SMES systems", *IEEE Transaction on Applied Superconductivity*, vol. 27, no. 2 , pp. 2324-2328, 2010.

[2] J. Zhu , H. Zhang , W. Yuan , M. Zhang , X. Lai," Design and cost estimation of superconducting magnetic energy storage (SMES) systems for power grids" published in *IEEE Power & Energy Society General Meeting* , Vancouver, 2013.

[3] G. Vyas , R.S. Dondapati, " AC losses in the development of superconducting magnetic energy storage devices", *Journal of Energy Storage*, vol. 27, 2020.

[4] Y.Xu *et al.* ," Distribution of AC loss in a HTS magnet for SMES in different operating conditions", *Physica C*, vol. 494, pp. 213-216, 2013.

[5] B. Shen, F. Grilli and T. Coomb," Review of the AC loss computation for HTS using H formulation", *Superconductivity*, vol. 33, no. 3 , 2020.

[6] H. Hosono, A. Yamamoto, H. Hiramatsu and Y.Ma," Recent advances in iron-based superconductors toward applications", *Materials Today*, vol. 21, no. 3, pp. 278-302, 2018.

[7] M. N.Wilson," NbTi superconductors with low ac loss: A review", *Cryogenics*, vol. 48, no.7-8, pp. 381-395, 2008.

[8] P.N. Barnes, M.D. Sumption, G.L. Rhoads," Review of high power density superconducting generators: Present state and prospects for incorporating YBCO windings", *Cryogenics*, vol. 45, no.10-11, pp. 670-686, 2005.

[9] L.Wang , J. Zheng , Y. Song, and Y. Wan," Multiscale Model for Simulation of Large-Scale YBCO Solenoid Coils With *J* Infinite-Turn", *IEEE Transaction on Applied Superconductivity*, vol. 29, no. 2 , 2019.

[10] Z. Zhang, L. Ren, Y. Xu, Z. Wang, Z. Wang and Y. Tang, " Numerical Multiscale model for AC loss Calculation of large scale HTS solenoid magnets", *IEEE Transaction on Applied Superconductivity*, vol. 28, no. 4 , 2018.

[11] S.S Peng, J. Zheng, W.Y Li and Y.J Dai," AC Loss Analysis of a Single- Solenoid HTS SMES Based on H- formulation", *IOP Conference Series: Earth and Environment Science*, vol. 233, no. 2, 2019.

[12] V. M. R. Zermeno, A. B. Abrahamsen, N. Mijatovic, B. B. Jensen, and M.P. Sorensen," Calculation of alternating current losses in stacks and coils made of second generation high temperature superconducting tapes for large scale applications", *Journal of Applied Physics*,vol. 114, no.17, 2013.

[13] M.Y. Asrami , W. Song, X. Pei , M. Zhang and W. Yuan," AC loss characterization of HTS pancake and solenoid coils carrying Nonsinusoidal Currents", *IEEE Transaction on Applied Superconductivity*, vol. 30, no. 5 , 2020.

[14] J. Zheng, S.S Peng, W.Y Li and Y.J Dai," Magnet design of 10 MJ multiple solenoids SMES", *IOP Conference Series: Earth and Environment Science*, vol. 233, no. 3, 2019.

[15] Z Hong, A M Campbell and T A Coombs," Numerical solution of critical state in superconductivity by finite element software", *Superconductor Science and Technology* , vol.19, no. 12, pp. 1246-1252, 2006.