Mathematical formulation on the Electro-Magnetic Losses in Superconducting Tapes used for Energy Storage Applications

Raja Sekhar Dondapati

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

ABSTRACT

It is a common belief that superconductors conduct electricity with no energy loss. In fact superconductors experience losses when transmitting an alternating current. Loss less transmission occurs for direct current transmission, but most of the power applications involve AC current and DC transmission requires costly converters at ends of transmission line so, most of the transmission lines are of AC. A high temperature superconducting power cable can transmit electric power with low loss when compared to conventional power cables. The most important aspect of an economic performance of the High Tc power cable is the refrigeration cost which depends on the AC losses. AC losses are classified as Hysteresis (Self and External field), Eddy current and Coupling losses.

INTRODUCTION

In recent past, Mukoyamaet al., reported about the AC loss measurement in the conductor with and without shield of HTS cable filled with LN_2 [1]. AC losses without shield can be calculated by using lock-in-amplifier.

$$Q'_{AC} = T^{-1}\int_0^T I(t)V(t)\,dt = \sum I(t)V(t) = I_e V_e \cos\theta \tag{1}$$

where, $I(t)$, $V(t)$ are current in the conductor and voltage difference voltage taps, I_e, V_e are the effective values of current and voltage and θ is phase difference between the $I(t)$, $V(t)$

In this method AC losses in each layer was derived by using the relationship between the current and voltage including the shield [2]

$$Q'_{AC} = \int_0^T V_C I\,dt + \int_0^T V_S I\,dt = IV_C\cos\theta_C + IV_S\cos\theta_S \tag{2}$$

where, V_C, V_S are the voltages in the conductor and shield between the ends

a) Joint part subtraction method

In this method voltage taps between the jointed ends of each conductor with shield in the total system are considered. AC losses are calculated by subtracting the system losses with jointed part AC losses [3]

$$Q'_{AC} = \int_0^T V_1 I\, dt - \int_0^T V_2 I\, dt = IV_1 \cos\theta_1 - IV_2 \cos\theta_2 \tag{3}$$

b) Joint part differential method

In this method the voltage between the voltage taps of one side of conductor, shield and other side joint part are considered. AC losses are calculated by using phase difference and differential voltage signal [4]

$$Q'_{AC} = I\left(V_1 - V_2\right)\cos\theta \tag{4}$$

where, V_1 and V_2 voltage between voltage taps of side 1 and side 2

The AC losses in the HTS tapes are given by following equations.

$$AC\,losses = W_{self} + W_{Ba} + W_{Bc} \tag{5}$$

Where, W_{self} = self field loss, W_{Ba} = axial field loss,

W_{Bc} = circumferential field loss

According to the Sumitomo's cable

$$W_{total} = W_{self} + W_B \,\text{(W/m)} \tag{6}$$

Where, W_B is equal to summation W_{Ba} & W_{Bc}.

According to Furukawa's cable

$$W_{total} = W_B + W_{self} + W_{eddy} \,\text{(W/m)} \tag{7}$$

Self field AC losses are calculated by using Norris Equation .

$$Qac = \frac{\mu_0 I_c^2 f}{\pi}\left[(1-\Gamma)\ln(1-\Gamma)+\Gamma-\frac{\Gamma^2}{2}\right]\text{W/m} \tag{8}$$

$$\Gamma = \frac{I_{pk}}{I_c} \qquad \text{For } \Gamma \ll 1 \tag{9}$$

$$Qac \cong \frac{\mu_0 I_c^2 f}{6\pi}\Gamma^3 \quad (10)$$

$$F_R = F_{field} . F_{strain} \quad (11)$$

$$I_{c,cable} = N . F_R . I_{c,tape} \quad (12)$$

$$I_{pk} = \sqrt{2} . I_{rms} \quad (13)$$

$$\Gamma = \frac{\sqrt{2} . I_{rms}}{I_{c,cable}} \quad (14)$$

$$P = V_{rms} \cdot I_{rms} \cdot \cos\phi \quad (15)$$

Where, Γ is the normalized current, F_R is retention fraction, N is the number of tapes in the cable, V_{rms} = RMS voltage (V), I_{rms} = Transport current (A), cosΦ = power factor.

1.1 Mathematical modeling for retaining the superconductivity of the superconducting material after the influence of critical parameters

1.1.1 Basic Parameters

Select the CC 1G/2G (YBCO or BSCCO) and specify the initial parameters at the ambient or base temperature (T_a) of the cryogenic liquid bath. The parameters such as minimum critical current @ T_a, critical temperature (T_α), width of conductor (w), thickness of conductor (t), critical current density (J_c), resistivity (ρ), conductor index number (n), specific heat (C_V) etc. For the simulation purpose fix the maximum fault limit time [7] it ranges from 80ms-120ms [8]. Behavior of superconductors can be studied from the J-B-T curve [6]. The critical values will change according to J (T), B (T)

The basic parameters on which the superconducting material design depends are [9]

1) Current

Relation between RMS current and peak current is

$$I_p = \sqrt{2} I_{rms} \quad (16)$$

Calculate current in the different layers of superconducting tapes.

2) Area of superconductor

$$A_{HTS} = w*t \tag{17}$$

The capacity of carrying current in SC tape increases if thickness of tape increases is stated by Yazawa et al [10] Area of tape in I_C and J_C is

$$A = \frac{I_c}{J_c(T)} \tag{18}$$

3) Length of tape

Electrical field expressed in length is

$$E = \frac{dv}{dl} \tag{19}$$

where, v is transmission voltage

Length of SC tape

$$L_{HTS} = \frac{\sqrt{2}V_{rms}}{E_{peak}} \tag{20}$$

Length of tape can calculated from equation **Error! Reference source not found.** by the parameters first peak current (I_{rp}) and SFCL resistance as follows [11]

$$l_{SC} = \frac{R_{SFCL}}{E_C} * \frac{I_C{}^n}{I_{rp}{}^{n-1}} \tag{21}$$

4) Number of windings over the mandrel

Turns depends on width of the tape, length of tape, diameter of the mandrel and the sense of winding

CONCLUSIONS

There are several prominent issues associated with SMES such as design related issues of superconducting coils, cooling up components of SMES, AC losses in superconducting tapes etc. Therefore, the available literature related to Superconducting Magnetic Energy Storage Devices can be divided among those issues. In this section a typical review on the aforementioned issues is presented and efforts are made to find out a technical gap for further research.

Superconducting coil can be developed in various configurations such as Solenoid type coil, Toroidal type coil, Pancake type coil, Double pancake type coil. Sometimes the solenoid configuration is developed by keeping pancake coil one over another axially. In double pancake coil, two pancake coils are connected to each other make one unit or module. Then these units are placed either in a solenoid configuration or in toroidal configuration depending upon the requirements.

REFERENCES

[1] H. Hayashi *et al.*, “Test results of power system control by experimental SMES,” *IEEE Trans. Appl. Supercond.*, vol. 16, no. 2, pp. 598–601, 2006.

[2] K. C. Seong, H. J. Kim, S. H. Kim, S. J. Park, M. H. Woo, and S. Y. Hahn, “Research of a 600 kJ HTS-SMES system,” *Phys. C*, vol. 465, pp. 1240–1246, 2007.

[3] a.-R. Kim *et al.*, “Operational Characteristic of the High Quality Power Conditioner With SMES,” *Appl. Supercond. IEEE Trans.*, vol. 18, no. 2, pp. 705–708, 2008.

[4] S. Kim, K. Sim, H. Kim, J. Bae, E. Lee, and K. Seong, “Thermal characteristics of conduction cooled 600 kJ HTS SMES system,” *Cryogenics (Guildf).*, vol. 49, no. 6, pp. 294–298, 2009.

[5] A. Kim *et al.*, “Operating Characteristic Analysis of HTS SMES for Frequency Stabilization of Dispersed Power Generation System,” vol. 20, no. 3, pp. 1334–1338, 2010.

[6] W. Yao, L. Jiang, J. Fang, J. Wen, S. Cheng, and Q. H. Wu, “Adaptive power oscillation damping controller of superconducting magnetic energy storage device for interarea oscillations in power system,” *Int. J. Electr. Power Energy Syst.*, vol. 78, pp. 555–562, Jun. 2016.

[7] J. Zhao, Y. Li, and Y. Gao, “3D simulation of AC loss in a twisted multi-filamentary superconducting wire,” *Cryogenics (Guildf).*, vol. 84, pp. 60–68, 2017.

[8] M. Erdogan, “Calculation of AC loss in two-layer superconducting cable with equal currents in the layers,” *Phys. C Supercond. its Appl.*, vol. 531, pp. 20–24, 2016.

[9] Y. D. Agassi, “AC losses in superconductors with a power-law constitutive relation,” *Phys. C Supercond. its Appl.*, vol. 517, pp. 41–48, 2015.

[10] Y. Xu *et al.*, “Distribution of AC loss in a HTS magnet for SMES with different operating conditions,” vol. 494, pp. 213–216, 2013.

[11] E. S. Otabe, S. Komatsu, V. S. Vyatkin, M. Kiuchi, T. Kawahara, and S. Yamaguchi, “Numerical estimation of AC loss in superconductors with ripple current,” *Phys. C Supercond. its Appl.*, vol. 494, pp. 173–176, 2013.