AC Losses and Material Degradation Effects in a Superconducting Tape for SMES Applications

Nuno Amaro, Ján Šouc, Michal Vojenčiak, João Pina, João Martins, J. Ceballos, Fedor Gömöry

AC Losses and Material Degradation Effects in a Superconducting Tape for SMES Applications

Nuno Amaro[1], Ján Šouc[2], Michal Vojenčiak[2], J. Murta Pina[1], J. Martins[1], J. M. Ceballos[3], Fedor Gömöry[2]

[1] Centre of Technology and Systems, Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, 2829-516 Caparica, Portugal
[2] Institute of Electrical Engineering, Slovak Academy of Sciences, Dúbravská cesta 9, 842 39 Bratislava, Slovak Republic
[3] "Benito Mahedero" Group of electrical Applications of Superconductors, Escuela de Ingenierías Industriales, Universidad de Extremadura, 06006 Badajoz, Spain

nma19730@campus.fct.unl.pt, {eleksouc, michal.vojenciak}@savba.sk, {jmmp, jf.martins}@fct.unl.pt, jmceba@unex.es, gomoelek@savba.sk

Abstract. Superconducting Magnetic Energy Storage (SMES) systems are one potential application of superconductivity in electric grids. The main element of such systems is a coil, made from superconducting tape. Although SMES systems work in DC conditions, due to highly dynamic working regimes required for some applications, AC currents can appear in the coil. It is then of utmost importance to verify the magnitude of these AC currents and take into account AC losses generated on the tape in the design phase of such system. To assure a proper operation, it is also necessary to know tape characteristics during the device lifetime, which in normal operation conditions can be of decades. Continuous thermal cycles and mechanical stresses to which the tape is subjected can change its characteristics, changing important quantities like critical current (I_C) and *n*-value. It is then also necessary to evaluate tape degradation due to these conditions. A study of AC losses will be here presented, for a short sample of BSCCO tape. I_C and *n*-value degradation due to consecutive thermal cycles will also be studied.

Keywords: Superconducting Magnetic Energy Storage, SMES, AC losses, HTS tape degradation.

1 Introduction

SMES systems are superconducting devices with several possible applications in electric grids and can contribute to the implementation of future's Smart Grids [1]. With such device it is possible to overcome several power quality issues, as voltage dips and swells, frequency oscillations or harmonic distortion [2]. This is possible because SMES systems store energy in a superconducting coil and can exchange active and reactive power, independently, with the electric grid where the system is placed. The main component of the system is a coil, made from high temperature superconducting (HTS) tape. This particular work will be focused in first generation (1G) tape, built by BiSrCaCuO on its phase 2223 (BSCCO/Ag tape).

Although the coil operates in DC conditions, highly dynamic regimes to which it is subjected can lead to the appearance of an AC current. This means that in the project phase of an SMES system, it is necessary to take into account phenomena that usually occurs in AC conditions, like AC losses [3]. In fact, AC losses are one of the limiting factors for large-scale applications of superconductivity in power systems. For several years, AC losses have been an important object of study in superconductivity in both, single tape samples and coils. As a very small example one can see references [4–6]. The study of AC losses in BSCCO/Ag tapes in self-field conditions is then of utmost importance for applications that use this superconducting material, and must be addressed in the firsts steps of any project. This study is extremely important because in the design phase of an SMES cooling system, one has to consider the necessary power to extract from the system heat generated by those losses. Considering that there are several possible applications of superconductivity (and of SMES systems in particular), it is also necessary to verify the frequency dependence of such losses, in order to achieve an accurate value for total AC losses in the system [7].

Bearing in mind an envisaged application for SMES systems where a highly dynamic regime can introduce AC currents in the coil with frequencies up to few hundreds Hz, in this work, a study with a frequency range from 72 Hz to 576 Hz will be presented.

It is common to model high temperature superconductors using the power law [8]:

$$E = E_C \left(\frac{J}{J_C} \right)^n \tag{1}$$

Where E is electric field in the superconductor, E_C is the value of electric field in which the critical current density J_C is achieved (a usual criterion of $E_C = 1\mu V / cm$ is used to define critical current). Parameter n is a material property and defines the shape of the E-J curve.

Operating conditions of superconducting devices in power systems subject HTS tape to various kinds of stress or strain. These can change tape characteristics, which will change important quantities like its critical current (I_C) or *n*-value. When subjected to bending and mechanical tension, the I_C value of a HTS tape will be degraded [9]. This fact should be taken into account in the design stage of the superconducting device, to assure a safe operation. To reduce mechanical vibrations in superconducting coils, it is common to impregnate HTS tape with epoxy. However, this impregnation may result in a higher tape heating, which can also decrease I_C [10].

In an SMES lifetime, the system can have many thermal cycles (cooling down and warming up the superconducting coil). These thermal cycles can also degrade the HTS tape, again leading to a lower I_c value [11] and possibly a different *n*-value. This effect will also be verified in this work.

2 Relationship to Collective Awareness Systems

Existing power grids are mainly unidirectional. However, in the electric grids of the future, energy is foreseen to flow up- and downstream. This "Smart Grid" concept involves both energy and information flows on the network [12]. This paradigm change transforms the power grid in a new grid, much more similar to information networks as internet. In the last years the concept of Internet of Things (IoT) in which every device is connected to the Web, is arising. Smart Grids represent a particular case of IoT, where reliability and security of supply are requirements of utmost importance, considering energy transmission and distribution. In this sense, power grids can become a Collective Awareness System, with distributed control and learning capabilities. Devices like SMES are foreseen to help the implementation of Smart Grids, thus being also part of these Collective Awareness Systems.

3 AC Losses in Superconducting Tapes

To verify the effects of AC losses in an SMES system it is first necessary to understand the origin of those losses and to classify them.

3.1 AC Losses Classification

Based on the physical mechanism that origins them and their frequency dependence, AC losses (power losses) in BSCCO/Ag tapes (and in HTS tapes in general) can be sorted into three different types [13]:

- *Superconducting hysteresis losses (P_h)*: linearly proportional to frequency, these appear due to variations in the superconductor magnetic state [14].
- *Eddy currents losses (P_{ed}):* due to the existence of silver in the BSCCO/Ag tape, there are Eddy currents through that metal, which also generates losses. These are quadratically proportional to frequency and, as demonstrated by Ishii et al. [15], can be expressed as:

$$P_{ed} = \frac{2\pi^2 \mu_0^{\ 2} f^2 I_p^{\ 2} d^3}{\rho l} \text{ (W/m)} \tag{2}$$

  where μ_0 is vacuum permeability, f is frequency, I_p is current amplitude through the tape, d is sheath thickness (for this tape: 36 μm), ρ is resistivity of silver (here set as $3\times10^{-9}\,\Omega.m$) and l is perimeter of the outer superconducting filament layer (in this case: 6.5 mm).
- *Resistive losses (P_r):* at high applied-to-critical current ratios (i), resistive losses appear in the superconductor. These are frequency independent and their value depends on the characteristics of the tape (mainly *n*-value). Usually they are negligible till i > 0.8 [13].

Total AC losses in the superconducting tape are then the sum of those three components. By dividing the power loss per meter (P) by frequency, one can achieve the energy loss per meter, per cycle (Q) as follows.

$$Q_t = \frac{P_t}{f} = \frac{P_h}{f} + \frac{P_{ed}}{f} + \frac{P_r}{f} = Q_h + Q_{ed} + Q_r \text{ (J/m)} \tag{3}$$

At frequencies below 200 Hz hysteresis energy losses (Q_h) are expected to have a main contribution. These are frequency independent. Eddy currents losses contribution for frequencies below this value are usually negligible, but they start to have a higher contribution to total losses with increasing frequencies. Resistive losses, as already stated, are frequency independent and depend on the used applied-to-critical current ratio. Their contribution to total losses is only visible for applied currents close to the tape I_C.

In this work, AC losses of a short sample of BSCCO/Ag tape, in which flows an AC current with frequencies ranging from 72 to 576 Hz, will be measured. The frequency dependence of these losses will be evaluated, especially concerning Eddy current losses, which are those most dependent of frequency.

To evaluate effects of thermal cycles in I_C and *n*-value, thus on operating conditions of the tape, after a first measurement of I_C, the sample is subjected to several of those cycles and critical current is measured again to obtain a comparison which can be very useful in real systems applications. By fitting all measured data to E-J power law (1) it will be possible to see if the *n*-value of the tape is also degraded.

4 Experimental Measurements of AC Losses

To evaluate tape degradation, the I_C of an HTS tape sample was measured prior and after several dozens of thermal cycles. AC losses were measured and compared to the well-known Norris ellipse model [14]. To evaluate frequency dependence, both total measured losses and calculated losses by taking out Eddy current component will be presented. It is expected that, after taking out the component related to Eddy currents, AC losses show no frequency dependence. InnoST insulated tape was used and its characteristics are shown in table 1.

Table 1. Characteristics of the SC tape, according to supplier.

Characteristic	Value
Critical current @ 77 K, self-field (A)	85
Critical current density (SC) (A/mm^2)	8500
Minimum bending radius (mm)	30
Width (mm)	4.2
Thickness (mm)	0.25

4.1 Experimental Setup

To measure I_C (DC critical current) and AC losses, a four-point configuration was used. Figure 1 depicts the used sample with voltage taps 4 cm apart. AC losses were measured using an electrical method with a lock-in amplifier as main measuring device and a Rogowski coil. All measurements were made at liquid nitrogen (LN) temperature (77 K).

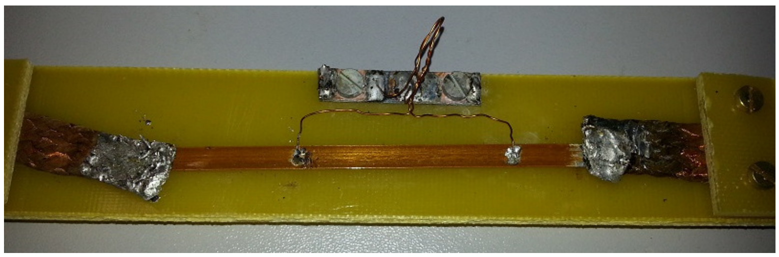

Fig. 1. HTS tape sample for measurements of critical current and AC losses.

4.2 Measurements of Critical Current

DC critical current was measured for three different tape conditions:

- Unused sample (*case A*);
- After 25 thermal cycles (*case B*);
- After a total of 50 thermal cycles (*case C*).

For every thermal cycle the tape was cooled down by putting the tape directly into LN and then warmed up to room temperature (warm up by natural heating, just by taking the sample out of LN). All results are shown in figure 2.

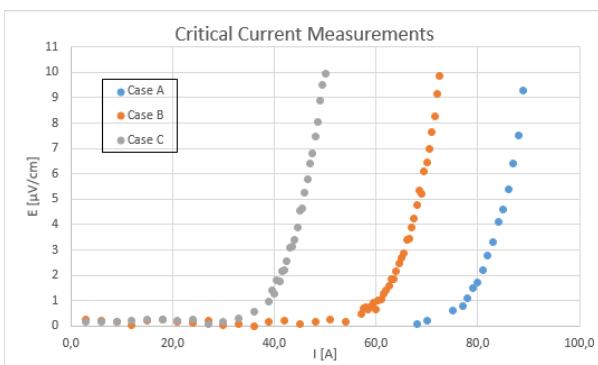

Fig. 2. Critical current measurements.

To evaluate critical current and *n*-value degradation, experimental results obtained for the three previous cases were used to achieve fitting E-J curves, by using Matlab® cftool. Results are shown in table 2.

Table 2. I_c and *n*-value degradation due to thermal cycles.

Number of cycles	Critical current [A]	*n*-value
0	77.02	15.35
25	59.6	11.73
50	37.9	8.44

As can be seen from results contained in table 2, the number of thermal cycles to which a superconducting tape is exposed degrade important characteristics like its critical current and *n*-value.

4.3 Measurements of AC Losses

AC losses were measured for four different values of frequency: 72 Hz, 144 Hz, 288 Hz, and 576 Hz. Figure 3 contains results for measurements made with the tape in situation B (after 25 thermal cycles). In this figure, Norris ellipse model is also shown for two values of critical current: 77 A and 60 A.

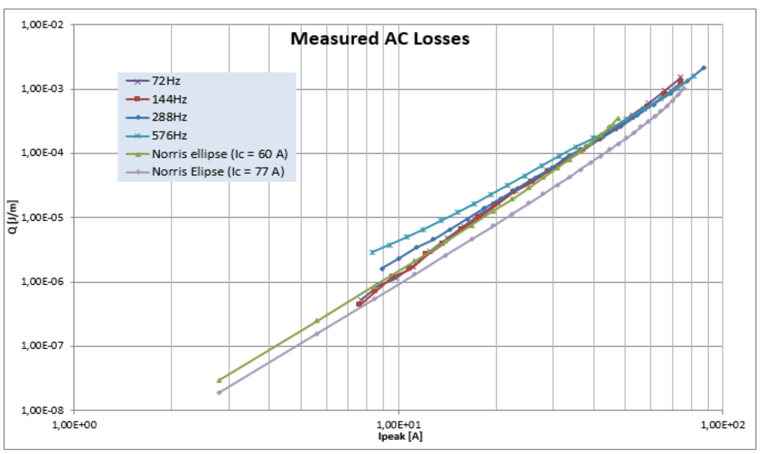

Fig. 3 Measured (total) AC losses

Results contained in figure 3 suggest that values tend to approach Norris ellipse model (for I_c = 60 A), for lower frequencies (72 Hz and 144 Hz) and for current values close to the critical current (for all frequencies). For small current amplitudes and when the current flowing through the tape has higher frequencies (288Hz and 576 Hz) AC losses seem to be frequency dependent, increasing with frequency. Eddy current losses should be responsible for this behavior. However, when the current increases resistive losses start to appear in the tape, making Eddy current losses negligible to the total losses value. So for currents whose peak is close to the critical current of the tape, there is no frequency dependence because resistive losses, which became the most important component in total losses (together with hysteresis losses) are frequency independent. As can be seen by the two Norris ellipse models depicted in the figure, for the same value of applied current, losses are higher if the tape has less critical current. This is an obvious result, since it means that for the same operating current, the tape is closer to its critical current if this value is lower. This also shows that AC losses in tapes with degraded critical current can still be modeled using Norris ellipse model, if the model is calculated considering the new value of critical current of that tape.

To verify if the frequency dependent behavior for small current amplitudes is due to Eddy current losses, this component was calculated using expressions (2), (3) and subtracted from the total value of losses. The results obtained are shown in figure 4.

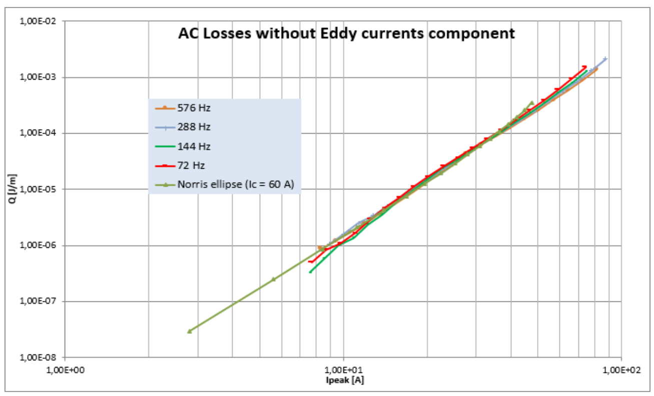

Fig. 4 AC losses after subtracting Eddy current losses component.

As can be seen in figure 4, AC losses show a non-frequency dependent behavior, if Eddy current losses are not considered. Norris ellipse model for a critical current of 60 A is also shown in this figure, for easier comparison with the previous one.

5 Conclusions

Critical current and *n*-value degradation due to thermal cycles in an HTS BSCCO/Ag tape was studied. As shown by experimental results obtained, these important quantities in a superconducting tape are effectively degraded if the tape is subjected to a certain number of thermal cycles. In fact, by subjecting the tape to a total of 50 cycles, there is a reduction of 50% of critical current value and the n-value changes from 15.35 to 8.44. This phenomena is of extreme importance for superconducting devices like SMES, where operating current is calculated based on critical current of the tape. This means that during the lifetime of the device, due to tape degradation, the required power to extract heat losses is expected to increase (for the same operating current) and this aspect cannot be neglected in the design phase of an SMES project.

AC losses of a short sample of degraded BSCCO/Ag tape, in which there are currents flowing in a band of frequencies ranging from 72Hz to 576 Hz were also measured. Results indicate that AC losses in HTS degraded tapes can still be modeled using Norris ellipse model, if the critical current of the model is set to the effective critical current of the tape after degradation. AC losses seem to behave as frequency independent for the measured frequencies, if Eddy current losses are subtracted from the total value. As expected, Eddy current losses are frequency dependent and can be neglected for frequencies below 200 Hz.

References

1. Amaro, N., Murta Pina, J., Martins, J., Ceballos, J.M.: SUPERCONDUCTING MAGNETIC ENERGY STORAGE - A Technological Contribute to Smart Grid Concept Implementation. Proceedings of the 1st International Conference on Smart Grids and Green IT Systems. pp. 113–120. SciTePress - Science and and Technology Publications (2012).
2. EURELECTRIC: Power Quality in European Electricity Supply Network, Brussels (2003).
3. Xu, Y., Tang, Y., Ren, L., Jiao, F., Song, M., Cao, K., Wang, D., Wang, L., Dong, H.: Distribution of AC loss in a HTS magnet for SMES with different operating conditions. Phys. C Supercond. 494, 213–216 (2013).
4. Ashworth, S.P.: Measurements of AC losses due to transport currents in bismuth superconductors. Phys. C Supercond. 229, 355–360 (1994).
5. Gömöry, F., Bettinelli, D., Gherardi, L., Crotti, G.: Magnetic measurement of transport AC losses in Bi-2223/Ag tapes. Phys. C Supercond. 310, 48–51 (1998).
6. Šouc, J., Pardo, E., Vojenčiak, M., Gömöry, F.: Theoretical and experimental study of AC loss in high temperature superconductor single pancake coils. Supercond. Sci. Technol. 22, 015006 (2009).
7. Yuan, J., Fang, J., Qu, P., Shen, G.X., Han, Z.-H.: Study of frequency dependent AC loss in Bi-2223 tapes used for gradient coils in magnetic resonance imaging. Phys. C Supercond. 424, 72–78 (2005).
8. Rhyner, J.: Magnetic properties and AC-losses of superconductors with power law current—voltage characteristics. Phys. C Supercond. 212, 292–300 (1993).
9. Kim, H.-J., Kim, J.H., Cho, J.W., Sim, K.D., Kim, S., Oh, S.S., Kwag, D.S., Kim, H.J., Bae, J.H., Seong, K.C.: AC loss characteristics of Bi-2223 HTS tapes under bending. Phys. C Supercond. 445-448, 768–771 (2006).
10. Polák, M., Kvitkovic, J., Janšák, L., Mozola, P.: The effect of epoxy impregnation on the behaviour of a Bi-2223/Ag coil carrying DC or AC current. Supercond. Sci. Technol. 19, 256–262 (2006).
11. Chen, D.-X., Luo, X.-M., Fang, J.-G., Han, Z.-H.: Frequency dependent AC loss in degraded Bi-2223/Ag tape. Phys. C Supercond. 391, 75–78 (2003).
12. E.U., E. union: European SmartGrids Technology Platform - Vision and Strategy for Europe's Electricity Networks of the Future. Office for Official Publications of the European Communities, Brussels (2006).
13. Stavrev, S., Dutoit, B.: Frequency dependence of AC loss in Bi(2223)Ag-sheathed tapes. Phys. C Supercond. 310, 86–89 (1998).
14. Norris, W.T.: Calculation of hysteresis losses in hard superconductors carrying ac: isolated conductors and edges of thin sheets. J. Phys. D. Appl. Phys. 3, 489–507 (1970).
15. Ishii, H., Hirano, S., Hara, T., Fujikami, J., Sato, K.: The a.c. losses in (Bi,Pb)2Sr2Ca2Cu3Ox silver-sheathed superconducting wires. Cryogenics (Guildf). 36, 697–703 (1996).