An electromagnetic method for measuring AC losses in HTS tapes without lock-in amplifier

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Abstract. The measurement of AC losses in high temperature superconducting tapes is a complex task due to the small magnitude of the quantities to detect, and to the difficulty to separate the inductive and resistive parts of the measured voltage. This work describes a different approach to the electrical measurement of AC losses, not requiring lock-in amplifiers for the signal processing. The system is based on the acquisition of the voltage and current signals from the sample and their projection on a reference signal, performing a Hilbert transform based treatment procedure. This method allows one to retrieve the harmonic components of the signals with a significant noise reduction, thus improving the quality of the results. The experimental set-up is applied to measure AC losses in different HTS tapes, using sinusoidal currents of different amplitude and frequency. The results are compared with those obtained on the same tapes at other laboratories.

1. Introduction
The technical interest in High Temperature Superconductors (HTS) is increasing since many studies are showing their great potential for use in high field magnets [1] [2] and power applications [3] [4] [5]. In electromagnets, current ramps and variable magnetic fields can generate losses of various types. Power applications in most cases involve the use of AC currents, which generate losses in the superconducting materials. Since the AC losses can reach relatively high values, depending on the conditions at which the superconducting material is operated. In the design phase of a superconducting device, it is therefore necessary to make accurate predictions of their intensity through both experimental tests and numerical investigations on the individual HTS tapes that make up the device [6].

The measurement of AC losses in individual tapes is not a trivial task, due to the very small magnitude of the quantities to detect, which might lead to significant alterations of the results. Experimental methods for AC losses can be subdivided into two main groups: calorimetric and electromagnetic. The first ones are insensitive to electromagnetic noise, but they require precise calibrations of the experimental equipment to achieve the adequate accuracy. The electrical AC loss measurement techniques are sensitive to electromagnetic noise, and usually rely on the use of lock-in amplifiers, which are suitable devices for the signal processing [7 - 9]. However, these devices have a non-
negligible cost and exhibit limitations in the number of harmonics of the measured signal to be filtered which can be obtained. Furthermore, the manufacturers do not usually make available the algorithms implemented in the lock-in amplifier, which might make it more difficult to interpret the results obtained.

This work describes a different approach to the electrical measurement of AC losses, not involving lock-in amplifiers for the data filtering. The paper describes the procedure involved in the data treatment for the determination of AC losses in the developed experimental setup. In particular, the precautions required to minimize the undesired noise during data acquisition are described. The algorithm adopted for the data processing and calculation of AC losses is then presented.

In order to validate the developed experimental procedures and data treatment methodology, the measurement results obtained in different working conditions on a 4 mm wide HTS YBCO tape manufactured by American Superconductors (AMSC) are presented and compared with those obtained on the same tape in other research laboratories and with analytical formulae.

2. Experimental set-up

The HTS tape used in this work is the American Superconductors (AMSC) Type 8501. Fig. 1 presents its cross-section with the dimensions of each layer [10]. It should be noted that the tape has a Ni-5at.%W ferromagnetic substrate, which significantly impacts the value of AC losses measured on the tape [11].

The tape sample has a length of 30 cm and it is tested on a rigid G10 straight support, while the distance between the two voltage taps is 8 cm.

The tape critical current in self-field at 77 K is equal to 102.3 A. This current was measured in between all tests of the experimental campaign, to ensure that the tape was not degraded. As is well known, the critical current of the tape also affects the AC losses.

![Figure 1](image.png)

**Figure 1.** Geometry of the cross-section of the AMSC Type 8501 tape.

The experimental set-up developed is aimed at applying an AC transport current to the tape and measure the corresponding transport losses; its basic scheme is presented in Fig. 2.

The AC current is generated starting from a Keysight 33500B waveform generator controlled by the user via LabView interface, so that the frequency and amplitude of the signal can be varied during the experiment. The generated signal is acquired through a PicoScope 4444 multichannel oscilloscope and will henceforth be referred as the reference signal. The signal is amplified by means of a QSC Audio GX5 power amplifier and then by a TA transformer in which the primary and secondary windings are inverted with respect to the normal operation of the device, so as to increase the transport current intensity. The current is measured through a coaxial shunt resistor and acquired as a voltage signal by
the oscilloscope. This type of current transducer minimizes the phase shift between the current flowing in the HTS tape and the obtained signal. This signal will be referred as the current signal. Finally, the voltage developed along the sample is acquired through voltage taps soldered onto the tape surface at a distance of 80 mm from each other. This signal will be referred as the voltage signal.

![Figure 2. Experimental set-up for AC current generation and data acquisition](image)

The configuration of the measurement circuit of the voltage arising between the two voltage taps is based on previous works reported in the literature: the two wires are brought to a distance from the central axis of the tape equal to about 3 times the half-width of the tape and are then twisted together [12 - 14]. The configuration of the measurement circuit of the transport current and all other signals was studied in order to minimize the area available for the linking of external electromagnetic fluxes which could alter the measured signals.

The duration of the data acquisition was selected to correspond to an integer number of periods. This choice avoids the problems of leakage when performing integral transformations (i.e. a Discrete Fourier Transform) in the signal processing.

If during the experiment there is no need to set the frequency of the AC current to a specific value, it is preferable to select a frequency expressed in Hz as a prime number, close to the desired frequency value (i.e. 47 or 51 Hz instead of 50 Hz). This choice partly mitigates the problem of the induced electromotive forces due to external electromagnetic fluxes linked to the measurement circuit, which are responsible for most of the electromagnetic noise. As a matter of fact, these fluxes are characterized by a frequency corresponding to either the network frequency and/or some of its higher order harmonics. When the frequency used in the experiment corresponds to a prime number, the first harmonics affected by a possible overlapping with a possible harmonics of the network frequency will be of a higher order than in case of selecting a non-prime number.

3. Signal processing technique

Once the measured signals have been acquired, it would be theoretically possible to calculate the AC losses simply by computing the average value of the product between the voltage and current signals. By averaging in time, the voltage signal component which is not in phase with the current should be automatically canceled out, thus allowing for the calculation of the active power corresponding to the losses.

However, the intensity of the signals, especially the voltage one, is usually so low that it can easily be covered by the external electromagnetic noise. Furthermore, although a rectilinear tape has a very small inductance, its electrical resistance in the superconducting state is practically negligible. The voltage signal is therefore almost in quadrature with the current signal. This feature makes the system more sensitive to possible phase shifting between the real signal and the acquired signal; the measurement of their in-phase components is therefore more complicated.
Despite the precautions taken during the signal acquisition to reduce the noise, these problems cannot be fully solved and remain relevant. It is therefore important to adopt a proper data post-processing technique to correctly remove the unwanted components of the acquired signals before performing the loss calculation. The procedure adopted in this work is based on the comparison between the current and voltage signals with the reference signal, to identify their harmonic content with respect to the frequency of the reference signal.

Initially, the reference signal is processed by means of an offset removal and normalization. This signal can then be considered as perfectly sinusoidal, i.e:

\[ \cos(\omega t) \]  

where \( \omega \) is the pulsation of the reference signal assumed free of disturbances.

The Hilbert transform [15] is then applied, which allows shifting the signal by a phase \( \pi/2 \), resulting in a signal of the type \( \sin(\omega t) \).

The signal is then multiplied by the imaginary unit \( -i \), which yields:

\[ -i \sin(\omega t) \]  

Finally, the terms obtained in (1) and (2) are summed up to obtain a signal of the type:

\[ \cos(\omega t) - i \sin(\omega t) \]  

which will be referred as the \textit{processed reference signal}.

This signal is then processed with the current and voltage signals to obtain their respective harmonic components. The steps described below can be applied separately to either the current or the voltage signals; each of them will be referred individually as the \textit{measured signal}.

Despite the measured signal should in theory be sinusoidal, because of the noise, this signal is deformed. Thus, it will be considered as a generic periodic signal of the type \( f(t) \), without reference to the sinusoidal behavior.

Each harmonic component of the measured signal is calculated separately, in order to express the function \( f(t) \) as the following sum:

\[ f(t) = \sum_{n=1}^{\infty} a_n \cos(n\omega t + \alpha_n) \]  

where \( a_n \) and \( \alpha_n \) are the amplitude and the phase shift of the \( n^{th} \) harmonics and \( \omega \) is the pulsation of the reference signal.

The calculation of each harmonic component consists in raising the processed reference signal (3) to the \( n^{th} \) power and multiplying it by the measured signal reported in (4). Then, the average value of this product in time is computed. It can be demonstrated that every term of the measured signal \( f(t) \) that does not correspond to the \( n^{th} \) harmonic is canceled out by this averaging process. In terms of equations, this is equivalent to state that:

\[ \langle f(t) \cdot [\cos(\omega t) - i \sin(\omega t)]^n \rangle = \langle a_n \cos(n\omega t + \alpha_n) \cdot [\cos(\omega t) - i \sin(\omega t)]^n \rangle = \frac{a_n^n}{2} [\cos(\alpha_n) + i \sin(\alpha_n)] \]  

Eq. (5) allows one to obtain the amplitude and phase of each harmonics; the process can be repeated for all desired harmonics. A convergence study is carried out regarding the minimum number of harmonics for which the calculation must be repeated to obtain a sufficiently accurate signal filtering. It is found that treating harmonics up to order 20 allows to reach the convergence of the method. However, by repeating the calculation for a higher number of harmonics, the computational
The burden of the method does not increase significantly. In the results presented in the following, the filtering procedure is repeated up to the harmonics of order 30. It should be noted that the lock-in amplifier typically applies a similar data treatment procedure to one single harmonic only. Once this procedure is applied to both the current and voltage signals, an inverse Fourier transform is computed to retrieve the signals in the time domain. By applying the same process to the current and voltage signals, the filtered signals obtained have the same time scale and do not require further operations to correct for the phase shifts unavoidably associated to any data acquisition system. Finally, the average value of the product of the two processed signals is computed to determine the value of AC losses. Dividing this term by the distance between the voltage taps yields the losses in W/m.

**Figure 3.** Voltage signal acquired before (blue) and after (red) the processing in the time domain. The experimental parameters are: max current equal to 91.6 A, frequency equal to 50 Hz and the distance between voltage taps equal to 8 cm.

**Figure 4.** Voltage signal acquired before (blue) and after (red dashed) the processing, in the frequency domain. The experimental parameters are: max current equal to 91.6 A, frequency equal to 50 Hz. The filtering technique is applied up to the harmonics of order 30. The figure is in semi-logarithmic scale.
Fig. 3 shows an example of application of the processing to the voltage signal. The acquisition was performed through the PicoScope 4444 oscilloscope, which has 4 differential inputs, 14-bit resolution and a full-scale voltage of 10 mV. In the considered test, the AC current peak value is set to 91.6 A at a frequency of 50 Hz. As shown in Fig. 3, the raw signal is affected by a significant amount of noise and it is therefore not possible to use it for the loss measurement. The signal obtained after processing is instead much cleaner from noise and suitable for use in the AC loss assessment. It should be noted that the time evolution of the signal is not perfectly sinusoidal due to the presence of the tape ferromagnetic substrate, which affects the results especially at high values of the ratio between AC transport current and critical current.

Fig. 4 shows the same signal presented in Fig. 3, but in the frequency domain. This highlights the effect of the processing technique on the signal harmonics. There is an evident noise reduction in terms of frequencies of the treated signal compared to the raw signal. In the treated signal there are no frequencies higher than 1500 Hz, as the filtering process was repeated up to the harmonics of order 30 of the acquired signal.

4. Experimental results
In this section, the results obtained with the developed setup and processing method are presented and compared with those obtained in other research laboratories by using lock-in amplifiers in the data acquisition system. The tapes tested at the University of Bologna (named lab1) and at the Southwest Jiaotong University, Chengdu, China (named lab2 [16]) have the same characteristics presented in section 2 and come from the same lot. The tapes analyzed at the Chinese Academy of Sciences, Beijing, China (named lab3 [11]) have the same characteristics presented in section 2 but come from a different lot. All tests were conducted at 77 K, in liquid Nitrogen.

The experiments were performed by varying the frequency from 19 Hz up to 997 Hz. The maximum amplitude of the AC current, hereinafter \( I_m \), was also varied in the different acquisitions.

![Figure 5](image_url)

Figure 5. Comparison with losses obtain in our laboratory (lab1) and the ones obtained by (a) lab2 [16], or (b) lab3 [11], varying frequency at different currents.

Fig. 5 presents a comparison between the experimental results obtained at the University of Bologna (lab1) and those found at the Southwest Jiaotong University, Chengdu, China (lab2, presented in [16]) and at the Chinese Academy of Sciences, Beijing, China (lab3, presented in [11]). Fig. 5(a) shows a good agreement between the loss values measured at lab1 and lab2. Fig. 5(b) shows a good agreement between the results at lab1 and at lab3. The plot shows that, as expected, the losses in W/m increase as the frequency increases. Since the analyzed tape is a composite one, the AC losses are not only due to
the superconducting layer, but they derive from different loss contributions of the various layers (i.e. ferromagnetic losses, resistive losses in the conventional metal layers etc.) [6] [11]. For this main reason, the measured losses do not vary linearly with the frequency.

Figure 6. Comparison between the AC loss per unit length obtained with the developed experimental setup (lab1) and the analytical results found at different transport current and frequencies.

Fig. 6 shows the results obtained with the proposed method by varying the current at different frequencies. The results are compared with the Norris analytical formula for thin strips [17]. Since the analytical formula takes into account only the losses in the superconducting layer, a difference between analytical and experimental data is expected. It is worth noting that the experimental results approach the analytical ones when the current $I_m$ is close to the tape critical current. This may be due to the fact that while the losses in the superconductor layer increase monotonically with the current, those in the ferromagnetic substrate increase up to a stabilized value when reaching saturation [11]. Moreover, it can be noted that for lower frequencies the difference between the experimental results and the analytical formulae decreases: in fact, the losses in the superconducting layer dominate on the other loss components at high current and low frequencies.

5. Conclusions
This work presents an electromagnetic method for measuring AC losses in HTS tapes which does not make use of the lock-in amplifier.

The experimental set-up was developed with great care to the electromagnetic noise minimization. The core of the data treatment procedure is the algorithm for reducing the electromagnetic noise of the acquired signals, which allows determining the component of the measured voltage in phase with the current signal.

The results obtained have been compared with those found at other laboratories and with analytical results. A good agreement is obtained between the results of different laboratories, showing the effectiveness of this methodology to assess the value of AC losses.

This method can be applied to measure the AC losses in HTS tapes of any type and study the dependence of the losses on the input current parameters.

The advantages of the presented methodology are the possibility to avoid the use of the lock-in amplifiers, to increase the number of signal harmonics treated for the noise reduction, and to have a better control on the reconstructed voltage and current signals.
References

[1] A. Ballarino, ‘Prospects for the use of HTS in High-field Magnets for Future Accelerator Facilities’, *Proc. 5th Int Part. Accel. Conf.*, vol. IPAC2014, pp. 6 pages, 2014.

[2] H. Maeda and Y. Yanagisawa, ‘Recent Developments in High-Temperature Superconducting Magnet Technology (Review)’, *IEEE Trans. Appl. Supercond.*, vol. 24, no. 3, pp. 1–12, Jun. 2014.

[3] J. X. Jin et al., ‘Enabling High-Temperature Superconducting Technologies Toward Practical Applications’, *IEEE Trans. Appl. Supercond.*, vol. 24, no. 5, pp. 1–12, Oct. 2014.

[4] X.-Y. Xiao, Y. Liu, J.-X. Jin, C.-S. Li, and F.-W. Xu, ‘HTS Applied to Power System: Benefits and Potential Analysis for Energy Conservation and Emission Reduction’, *IEEE Trans. Appl. Supercond.*, vol. 26, no. 7, pp. 1–9, Oct. 2016.

[5] J. X. Jin et al., ‘HTS Power Devices and Systems: Principles, Characteristics, Performance, and Efficiency’, *IEEE Trans. Appl. Supercond.*, vol. 26, no. 7, pp. 1–26, Oct. 2016.

[6] F. Grilli, E. Pardo, A. Stenvall, D. N. Nguyen, Wei jia Yuan, and F. Gomory, ‘Computation of Losses in HTS Under the Action of Varying Magnetic Fields and Currents’, *IEEE Trans. Appl. Supercond.*, vol. 24, no. 1, pp. 78–110, Feb. 2014.

[7] R. Pei, A. Velichko, Y. Jiang, Z. Hong, M. Katayama, and T. Coombs, ‘High-precision digital lock-in measurements of critical current and AC loss in HTS 2G-tapes’, in *2008 SICE Annual Conference*, 2008, pp. 3147–3150.

[8] S. K. Olsen et al., ‘Alternating current losses of a 10 metre long low loss superconducting cable conductor determined from phase sensitive measurements’, *Supercond. Sci. Technol.*, vol. 12, no. 6, pp. 360–365, Jun. 1999.

[9] B. Shen et al., ‘Power dissipation in HTS coated conductor coils under the simultaneous action of AC and DC currents and fields’, *Supercond. Sci. Technol.*, vol. 31, no. 7, p. 075005, Jul. 2018.

[10] P. Zhou et al., ‘Frequency-Dependent Transport AC Losses of Coated Superconductors Up To Tens of Kilohertz’, *IEEE Trans. Appl. Supercond.*, vol. 29, no. 5, pp. 1–5, Aug. 2019.

[11] G. Liu, G. Zhang, H. Yu, L. Jing, L. Ai, and Q. Liu, ‘Experimental and numerical study of frequency-dependent transport loss in YBa$_2$Cu$_3$O$_7$-δ coated conductors with ferromagnetic substrate and copper stabilizer’, *J. Appl. Phys.*, vol. 121, no. 24, p. 243902, Jun. 2017.

[12] A. M. Campbell, ‘AC Losses in High Tc Superconductors’, *IEEE Trans. Appl. Supercond.*, vol. 24, no. 1, pp. 682–687, Jun. 1995.

[13] J. R. Clem, M. Benkraouda, T. Pe, and J. McDondald, ‘Penetration of Magnetic Flux in Electrical Current Density into Superconducting Strips and Disks’, *Chinese Journal of Physics*, vol. 34. No. 2-11, pp. 284–290, Apr. 1996.

[14] Y. Yang, T. Hughes, C. Beduz, W. T. Norris, and D. M. Spiller, ‘The influence of geometry on self-field AC losses of Ag sheated PbBi2223 tapes’, *Physica C*, vol. 256, pp. 378–386, 1996.

[15] A. W. Oppenheim, and R. W. Schafer, 'Discrete-time signal processing', Third edition, Prentice Hall, 2010.

[16] P. Zhou, G. Ma, and L. Quéval, ‘Transition frequency of transport ac losses in high temperature superconducting coated conductors’, *J. Appl. Phys.*, vol. 126, no. 6, p. 063901, Aug. 2019.

[17] W. T. Norris, ‘Calculation of hysteresis losses in hard superconductors carrying ac: isolated conductors and edges of thin sheets’, *J. Phys. Appl. Phys.*, vol. 3, no. 4, pp. 489–507, Apr. 1970.