AC LOSSES MEASUREMENTS IN HTS COILS

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Abstract

The possibility of production of the coils based on high-temperature superconductors (HTS) for accelerator applications is now under preliminary study in many accelerator centers and laboratories. The alternating magnetic field in these magnets causes energy dissipation (AC losses). The accurate measurement of AC losses is important for a comparison choice among different HTS conductors and for estimations of the total level of losses into final magnet too.

This article presents the measurement of transport AC losses (i.e. the losses in magnetic field which is generated by the alternating transport current) in HTS coils. Two model HTS coils with the racetrack geometry have been fabricated from 2nd generation HTS conductor supplied by two vendors. The measurement was performed by electrical method at the sinusoidal current with the amplitude up to 32 A and at the frequencies lain into interval from 5 up to 100 Hz. The measurement scheme and results are presented.

INTRODUCTION

Last years the possibility of use of high-temperature superconductor (HTS) coils for accelerator applications is under elaboration in many accelerator centers [1-4]. The unique properties of HTS can be utilized in magnets which produce very high fields (20 – 50 T) or magnets which operate at elevated temperatures (20 – 77 K). Also the fast cycling magnets have large interest. The alternating magnetic field in these magnets causes energy dissipation (AC losses). In practice about 0.1 - 0.01% of the energy saved in coil dissipates. The level of the AC losses becomes one of the main criteria at the development of superconducting magnets.

Two methods are usually applied for measurement of AC losses: calorimetric and electric [5]. The first method for racetrack HTS coils is described in [6]. It based on measurement of volume of the gas evaporated from liquid nitrogen due to dynamic losses. It is complicated and it demands the big expenses of time to attain the stationary condition, accounting of parasitic heat leakages and additional calibration.

The electric method is simpler and demands less time. Usually the inductive component of voltage on HTS coil is delivered from with the help of mutual inductance coil. Further the compensated signal was measured by the high-precision data acquisition system [6]. AC losses are obtained by integration of the product of voltage on a coil and current through a coil for one cycle. In the case of sinusoidal current the voltage on HTS coil is measured which is in phase to current. For this purpose the lock-in amplifier is used [7]. The power of AC losses is equal to the product of this measured voltage and current.

APPARATUS

The scheme of apparatus is presented in Fig. 1.

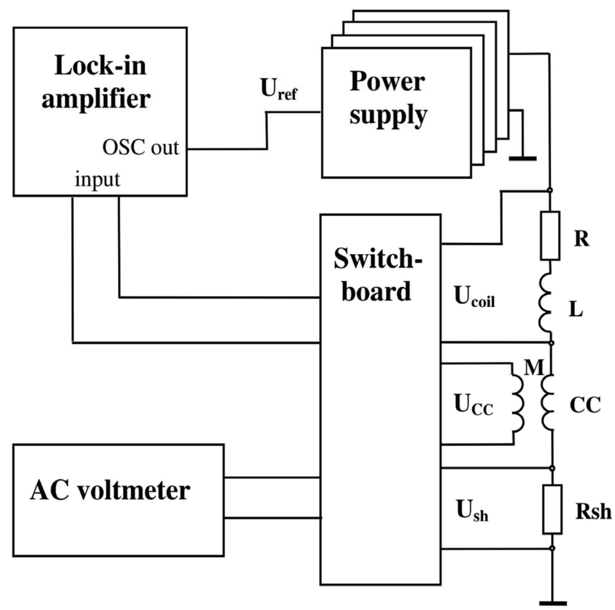

Figure 1: Electric scheme of apparatus for AC losses measurement in HTS coil.

The tested coil was powered by four operational power supplies (three KEPCO BOP 50-8M and one BOP 36-12M) connected in parallel and operated in the mode of current stabilization. For measurement of a current the AC voltmeter and 20A/75mv shunt are used. For obtaining the compensating voltage of the necessary value with a small shift of a phase and low noise the compensation coil CC has been manufactured. All its structural components were made of nonmagnetic materials. The frames of coils were made of glass-cloth-base laminate. The primary winding of the coil was made of the copper conductor with the cross section of 4.5 mm^2 in the glass tape insulation. It is wound in two layers on a frame with the outer diameter of 102 mm and has a length of 60 mm. The primary winding contains 39 turns. The secondary winding is wound by a copper wire with a diameter of 0.15 mm with enamel insulation on the frame with the diameter of 93 mm. It has the same length and contains 3024 turns. The secondary winding is inserted in primary winding and can move along axis with the help of a screw rod. The necessary value of coefficient of a mutual induction is tuned by mutual disposition of the coils and it can vary from 1.5 up to 7.8 mH.

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The switchboard was built on base of Agilent 34970A with multiplexer cards Agilent 34901A and Agilent 34903A. It connects the electric signals such as the voltage on the HTS coil U_{coil}, the voltage on secondary winding of the compensation coil U_{CC}, their differential voltage, and also the voltage from the current measuring shunt U_{sh} to the input of the lock-in amplifier and/or to the input of the AC voltmeter. EG&G Princeton Applied Research 5210 lock-in amplifier was used. A digital built-in voltmeter of data acquisition system Agilent 34970A was used as AC voltmeter.

MODEL COILS

The racetrack two-layer coils have been made for experimental study of losses on an alternating sinusoidal current. The coils have been made from HTS-2G tapes produced by the AMSC and SuperOx companies. The coils have been made in two options: in the first case core was manufactured from the steel of 30 HGSA grade, in the second case the core of the same geometry from glass-cloth-base laminate was used. For making of the coils with different cores the same piece of HTS-2G tape was used. It was wound consequently on various cores. The length of straight part is 245 mm and inner radius is 21.5 mm for both coils. Other coil characteristics are presented in Table 1. Critical current was measured at voltage corresponded to 1 μV/cm criterion. It was degraded after rewinds of coil.

Table 1: Characteristics of HTS Coils

Coil	1	2
HTS-2G tape	AMSC	SuperOx
Critical current of original tape at 77 K (A)	103	188-207
N-factor of tape at 77 K	34	40
Critical current of coil (A)	67.7	75
Critical current of coil after rewinds (A)	37.1	67
Width of tape (mm)	4.8	4
Thickness of tape (mm)	0.2	0.1
Number of turn in coil	40×2	60×2
Outer radius (mm)	35.2	34.5
Length of tape in coil (m)	~ 50	~ 80
Inductivity with nonmagnetic core (mH)	1.7	3.9
Inductivity with steel core (mH)	2.6	6.3

RESULTS OF MEASUREMENTS

Results of measurement of AC losses at a frequency range from 5 to 100 Hz and a current amplitude up to 35 A are presented in Figs. 2 and 3 for coils made from AMSC and SuperOx tapes without the iron core.

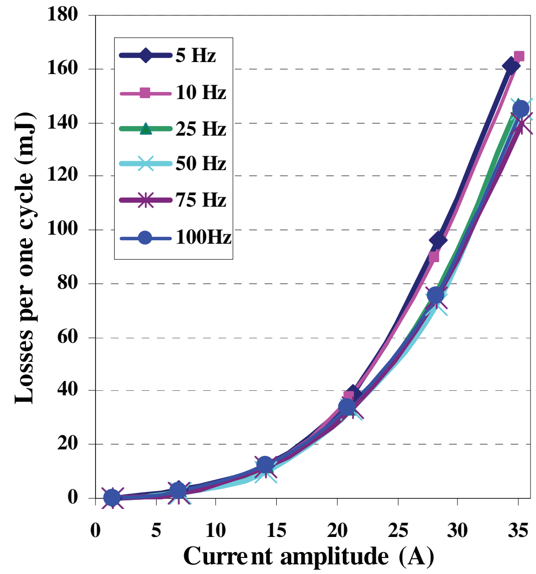

Figure 2: Dependence of AC losses on current in AMSC coil without the iron core.

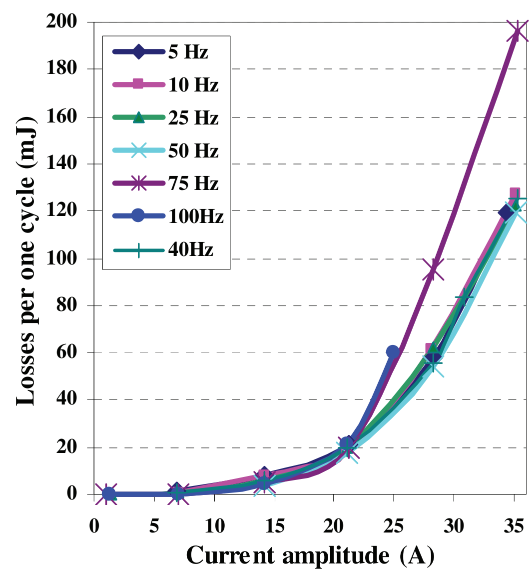

Figure 3: Dependence of AC losses on current in SuperOx coil without the iron core.

It is evident from these figures that in coils without the iron core the losses per one cycle poorly depend on frequency. The curves follow closely enough, and up to current amplitude of 20 A all curves coincide. It means that AC losses are defined by a hysteretic character of a magnetization of a superconductor. Values of AC losses in the coils without the iron core are in agreement with results of measurements obtained by other authors in the similar HTS coils [7 – 9]. In coils made from SuperOx tapes at current more than 20 A and a frequency over 50 Hz AC losses increase considerably that speaks about increasing of the eddy current component of losses. In this coil this component of AC losses has to be shown stronger such as the coil has more turns and therefore a greater magnetic field and a larger amount of conductor.

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Results of measurement of AC losses in coils with the iron core are presented in Figs. 4 and 5.

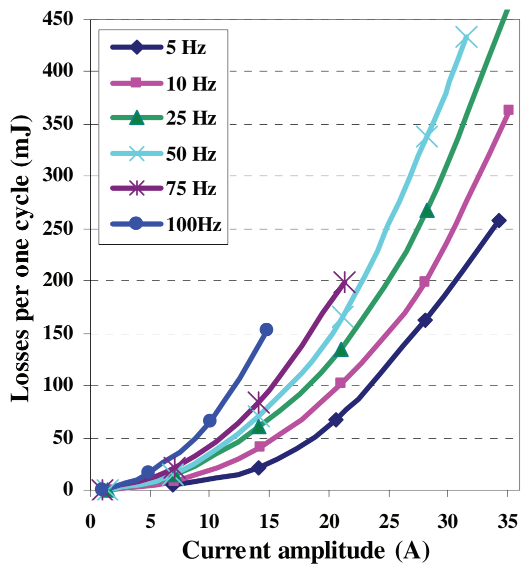

Figure 4: Dependence of AC losses on current in AMSC coil with the iron core.

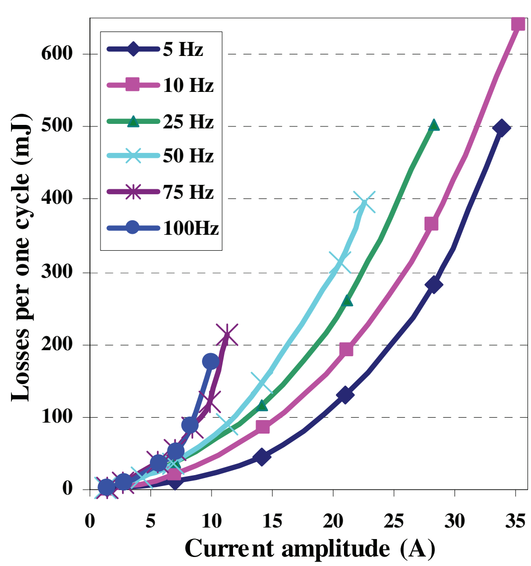

Figure 5: Dependence of AC losses on current in SuperOx coil with the iron core.

When coil had the iron core, the AC losses became approximately one order of magnitude more than in the coil without core because the components of AC losses are added which are related with hysteretic magnetization of the iron core and with eddy currents in the core. Observed strong frequency dependence means that there is a very large component related with eddy currents in the iron core. This component begins to prevail over all other components of losses already at a frequency of 25 Hz. It is possible to lower it by manufacture the core from the laminated steel. Losses in a coil made from SuperOx tape are higher. That is related to 1.5 times larger number of turns.

CONCLUSIONS

The apparatus for measurement of AC losses in HTS coils powered by alternating sinusoidal current with amplitude up to 35 A and frequency up to 100 Hz was created. Losses were measured in model coils made from HTS-2G tapes of AMSC and SuperOx manufacturers.

In coils without the iron core the losses per cycle poorly depend on a frequency and all curves coincide up to value of current amplitude of 20 A. At the current more than 20 A and at the frequency over 50 Hz the AC losses per cycle in the coil made from the SuperOx tape considerably increase that tells about increase of a component related with an eddy current. In coils with the iron core the losses become approximately one order of magnitude greater than in a coil without the core because of the hysteretic magnetization of the iron core and eddy currents in the core. It is possible to decrease the last one by making the core from the laminated steel.

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