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## AC losses test of HTS racetrack coils for HTS motor winding

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**Abstract.** Current work is dedicated to determination of AC losses of racetrack coils that are intended to be used in HTS motor winding. Coils were tested at temperature of boiling nitrogen with sine waveform current with frequencies from 50Hz to 200Hz and corresponding levels were taken as a basis for comparison. Current waveforms, distinctive for brushless DC and brushless AC motors, induced by high-frequency modulation, were compared. Two coils with same dimensions and numbers of turns, but with different tapes (AMSC/SuperOx) were compared in terms of the levels of losses on described current forms.

### 1. Introduction

High-temperature superconductors (HTS) are being widely used in DC applications like slow-cycling magnets or winding of DC electrical motors [1,2]. Typical AC usage of HTS conductors is power-grid cables or wind generators where current frequencies are concentrated mostly from several Hz up to 50..60Hz frequency. On the other hand, electrical machines with superconducting windings working on AC are very promising for the growth of specific parameters (kW/kg, kW/m<sup>3</sup>) [3]. Such advantage opens the capability to use HTS motors in the propulsion system of a small unmanned aircraft (UAV) but raises several problems. The first problem is the significant growth of phase current main frequency in medium- and high-speed motors and generators reaching hundreds of Hertz. The other problem comes from a power source of typical small-size UAV with an electric power plant: the battery.

A power inverter, so-called “electronic speed controller” (ESC) is indispensable in such setup to drive a brushless AC motor. Such devices apparently use an electronic circuitry called a voltage inverter for changing the polarity of a voltage applied to each phase, and a voltage level regulator (VR) to control the motor by two terms: phase frequency (via an inverter) and phase voltage (via voltage regulator). In stationary applications, the VR is often represented by a switching regulator module. However, in the autonomous vehicles, especially UAV, mass reduction is extremely important, so the function of VR is implemented in the voltage inverter circuit by terms of high frequency 1...100kHz pulse-width modulation or similar techniques[4].

Another important aspect of ESC and motor performance besides PWM is a current waveform that in many terms relies on motor type: brushless DC (BLDC) or brushless AC (BLAC) motors also referred to as permanent magnet synchronous motors or PMSM [5]. The difference between those types is the back electromotive force (EMF) waveform. BLDC motors are typically designed to produce a trapezoidal back EMF, while BLAC motors have a sinusoidal back EMF. The waveform of



back EMF is important because it specifies the commutation and control methods implemented in ESC.

In this article two 2G HTS coils, made from different tapes, were tested on a specially designed test bench with two distinctive current waveforms: “trapezoidal” (BLDC motors); and “sine” (BLAC motors). Losses levels are compared to a pure sine current at corresponding frequencies. All experiments were run at the temperature of boiling liquid nitrogen (LN<sub>2</sub>) at open bath cryostat.

## 2. Parameters of HTS coils and initial tests

Preliminary electromagnetic study of a 3kW HTS brushless motor for UAV purposes was performed, the main design points are shown in table 1. Two coils with the same winding parameters, but from different 2G HTS tapes were manufactured for the experiment. Winding parameters are summarized in table 2.

**Table 1.** Motor parameters.

Parameter	Value
Output power,kW:	3
Pole pair number:	2
Main harmonic frequency, Hz	200
Phase current amplitude, A	55
Phase turns	48
Coils per phase	2
Active length,mm	70

**Table 2.** Coil Dimensions.

Parameter	Value
Type	Double pancake
Inner radius, mm	10
Axial length, mm	70
Number of turns	24
Total wire length, m	5

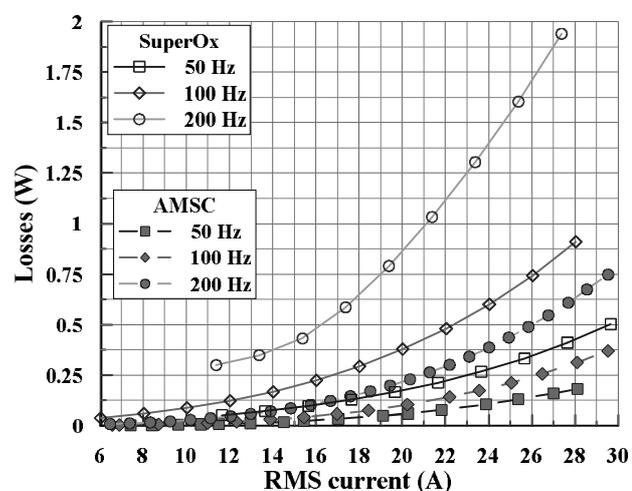
Prior AC tests the critical current ( $I_c$ ) was measured and a power-law index ( $n$ ), calculated from voltage-ampere curve  $E(I)$  of each coil was determined:

$$E(I) = E_c \left[ \frac{I}{I_c} \right]^n, \quad (1)$$

where  $E_0 = 1\mu\text{V/cm}$  is the electric field when the  $I_c$  is reached. The coil made from SuperOx 2G tape, compared to AMSC 2G tape showed significant degradation of critical current and  $n$  rise factor showing significant degrading effects of winding on a small carcass radii (table 3).

**Table 3.** Tape and coil parameters.

Parameter	AMSC	SuperOx
Average thickness, mm:	0.21	0.11
Maximum width, mm	4.95	4.1
$I_c$ (short sample), A	100	150
$n$ (short sample)	>30	>30
$I_c$ (coil), A	83	23
$n$ (coil)	23	3

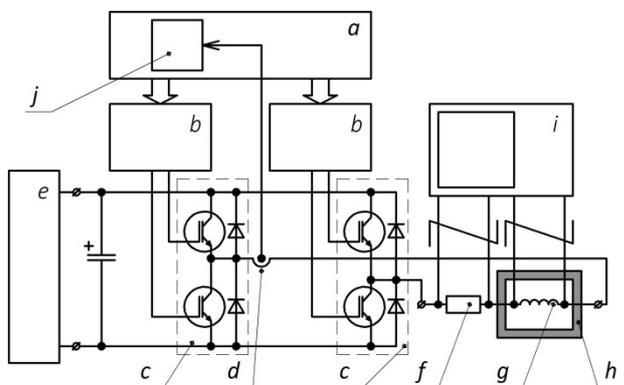


**Figure 1.** Pure sine current losses comparison.

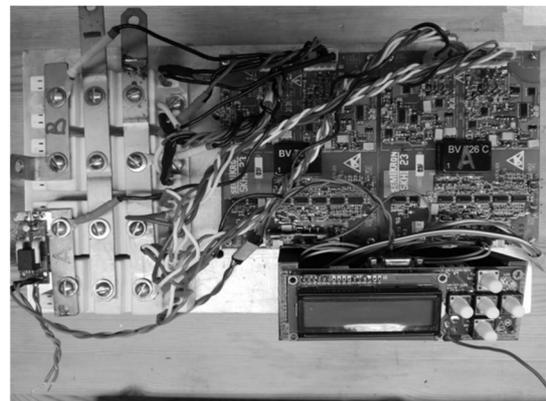
Despite relatively low critical current of the SuperOx coil, all of the planned tests were performed. At first, losses of each coil were determined on a pure sinusoidal current with frequencies 50, 100 and 200Hz, using the previous [6] measurement setup. The results are shown in figure 1; AMSC coil shows predictable high losses levels due to MOD/RABiTS™ manufacturing process with NiW substrates that have weak ferromagnetism.

### 3. BLAC and BLDC currents emulation setup

As it was claimed in the Introduction, currents in motors driven by ESC have strong high-frequency pulsations due to PWM or similar voltage regulation. A special test bench was designed to drive a single coil as it was a part of a motor winding. The structure of the setup is shown in figure 2, and the photo in figure 3. The generation of special form current is provided by H-bridge inverter with microprocessor control. It is based on two IGBT modules (c) each one consisting of two transistors with built-in reverse diodes. Special driver modules (b) control the gates of the transistors. Microprocessor board (a) forms the correct commutation sequence for each transistor. Laboratory supply (15V/100A) powers the IGBT bridge (e). The control board uses AVR ATmega128 microcontroller. Hysteresis (also known as bang-bang) algorithm [7] has been implemented to control the current in the coil under test (g) placed in a cryostat (h). The feedback signal is picked up by the hall-type current sensor (d) to the microcontroller's ADC (j). Every 16 microseconds the current level from the sensor is compared to a pre-programmed one, thus the microcontroller forms necessary control signals for the transistors. The unavoidable drawback of this algorithm is a floating current ripple frequency, which average value during experiments was about 6...8kHz. The bench is capable to drive any arbitrary current waveform (programmed by 127 points per period) with the main frequency up to 400Hz and instantaneous current value up to 50A.



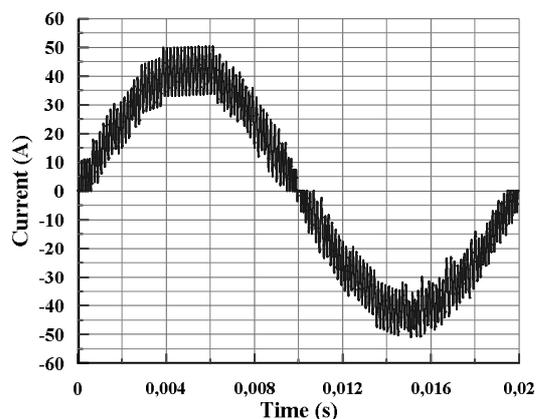
**Figure 2.** BLAC and BLDC currents emulating bench.



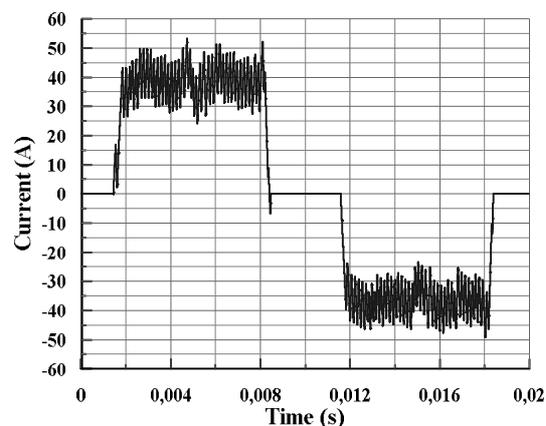
**Figure 3.** Photo of inverter assembly.

The device was programmed with two forms of current: sine wave (figure 4) and BLDC (figure 5). The BLDC waveform was captured from phase current of 200A “Flier” ESC, intended for use at large scale model aircraft or manned paraglider. The ESC was connected to a convenient, non-superconducting BLDC motor.

Losses levels were measured at the same frequencies as for pure sine waves, i.e. 50, 100 and 200Hz for easy comparison.



**Figure 4.** BLAC sine current in HTS coil at 50Hz main frequency.



**Figure 5.** BLDC trapezoidal phase current in HTS coil at 50Hz main frequency.

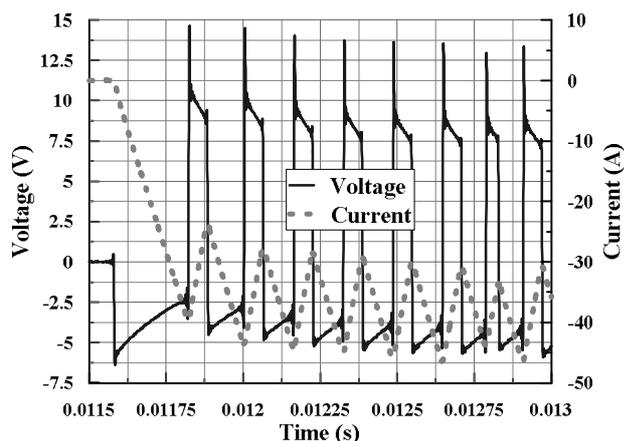
#### 4. Losses evaluation, results and comparison

The direct electrical method (figure 2), when the current (f) and potential voltage (g) are measured and recorded simultaneously by the data acquisition system (i), was implemented. The DAQ is Yokogawa DL850 with 1MS/s sampling rate and current sensor is a specially designed current shunt (f) with less than 5nH parasitic inductance. According to its' definition, active power, corresponding to energy transformed into heat on a dedicated part of an electrical circuit is determined by the formula [8].

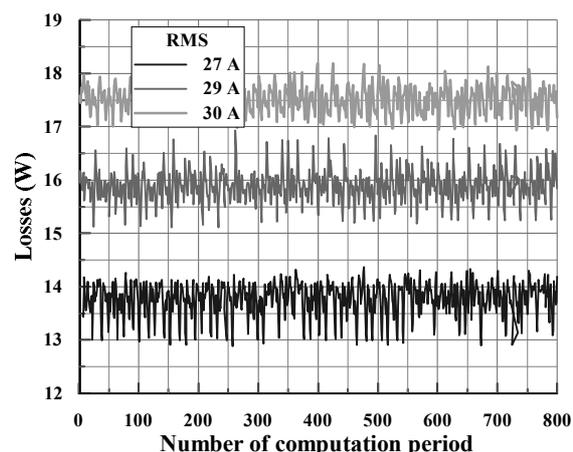
$$P = \frac{1}{t_m} \int_0^{t_m} u \cdot i dt, \quad (2)$$

where  $u$ ,  $i$  – instantaneous values of current and voltage,  $t_m$  – measurement time (period of signal).

The method, showing great results at smooth noiseless signals of voltage and current [6,9] should be used with extreme care for noisy conditions.



**Figure 6.** Voltage on HTS coil and current in it.

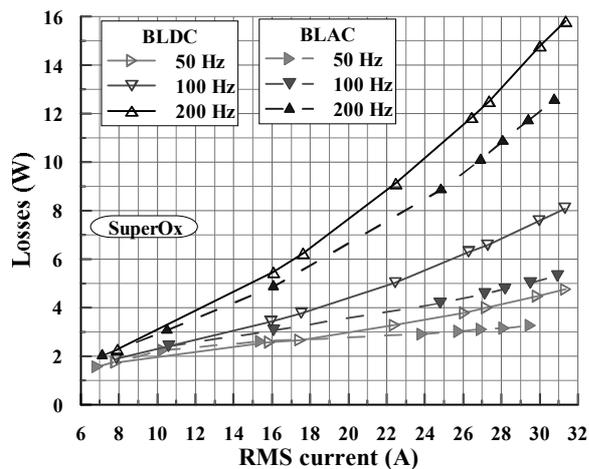


**Figure 7.** Power losses versus periods for 3 current levels at 200Hz BLDC current.

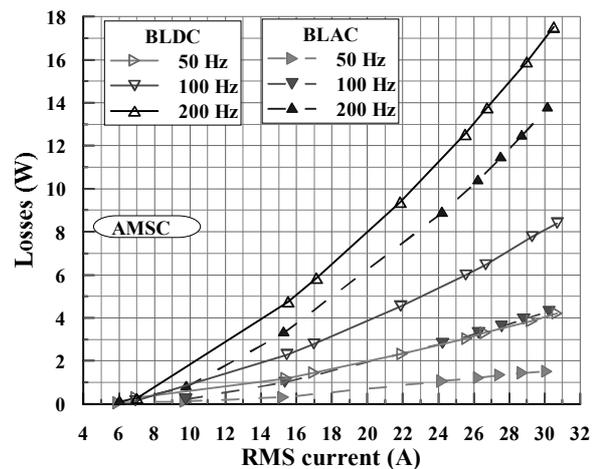
One can see the signal from voltage taps (figure 6) and corresponding current, depicting time interval corresponding negative half-wave beginning of current shown in figure 5. Voltage has a lot of additional peaks and glitches. To ensure calculations against possible mistakes caused by radio-

frequency bandwidth noises, periods of the signal were determined by zero crossings of the first harmonic of the current. Further, the recorded current and voltage signals were quantized using those time marks. Losses were calculated on each of obtained (200...800) periods, to get an average value and minimize errors. Figure 7 shows the calculated losses versus the period number for three current levels. All possible sources eliminating high-frequency noise coupling like signal and power paths, shielding, filtering, and so on were revised to achieve predictable and clear results.

Finally, the experimental results are shown in figure 8 and figure 9 for SuperOx and AMSC coils respectively. Losses are monotonically increasing in a similar manner compared to pure sine, but the values are many times higher.



**Figure 8.** SuperOx coil losses for BLAC and BLDC currents.



**Figure 9.** AMSC coil losses for BLAC and BLDC currents.

Most probably, the significant losses growth is connected to persistent 6...8kHz current ripple [10]. The amplitude (or current band) of the oscillations does not depend on the frequency and waveform of the coil current and fixed by the test bench current control loop. For the trapezoidal (BLDC) coil current, the losses increase even more, apparently because of higher harmonics complex ( $x_2$ ,  $x_3$  and more than main frequency).

## 5. Conclusion

Two coils from different HTS tapes were manufactured and tested with AC currents of various forms and frequencies. These coils are involved in the design of HTS motor for automotive usage, thus intended to be used with some kind of power electronics. Such a bundle of motor and electronics has two main branches: BLAC and BLDC. The experiments with coils driven by corresponding current types were carried out. Frequencies and current levels match the values for 3kW HTS motor design. One of the goals of this work was to choose the appropriate 2G HTS tape type and manufacturer for the motor winding. Despite significant  $I_c$  degradation of SuperOx tape after it was wound in a coil, it shows a certain advantage in terms of AC losses over AMSC coil, keeping almost negligible levels even at 200Hz.

The experiment with modulated currents changed the situation drastically. One can see that the power losses are almost equal for both coils at the highest currents and frequencies. 100 and 200Hz regimes at RMS currents of 25A and higher represent the nominal power operating mode of the purposed HTS motor. In terms of a real HTS machine, the overall growth of losses (from negligible several watts to dozens of watts) in winding would not really affect the efficiency of the 3kW motor. Moreover, in a real machine, there will be additional sources of losses like eddy currents in the ferromagnetic stator core, etc. And the losses in coils will grow even more due to higher magnetic

fields. Nevertheless, the presented work clearly shows that losses at BLDC/BLAC modes are no more negligible. Special arrangements in the motor design should be done to organize stable LN<sub>2</sub> flow to eliminate overheating of HTS winding and switching it to normal mode.

### Acknowledgements

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