Development of 10kWh Flywheel Energy Storage System

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SUMMARY

We have designed and manufactured a flywheel energy storage system (FESS). The system has a flywheel made of carbon fiber reinforced plastics (CFRP) of the diameter of 1m supported by active magnetic bearings (AMB) of low energy loss. The flywheel rotor can be accelerated to 17,200rpm by a synchronous motor. The rated capacity of the energy storage system is 10kWh.

The energy loss of AMB is measured by using a test rig, which is designed to minimize the energy loss of AMB. Results obtained by free-running tests up to 12,000rpm show that the energy loss of the homopolar AMB is smaller than that of the heteropolar AMB. The energy loss of the homopolar AMB is found to be about 75W for one unit of the AMB with the bias current of 1.5A at 12,000rpm.

The present paper shows details of the energy loss of the test rig equipped with three types of the AMB, and also presents some of the measured data of the 10kWh FESS.

INTRODUCTION

Recently, energy storage systems at distributing substations are needed in order to level off daily fluctuations of loads on electric power, because of increasing electric power demands. A FESS is believed to be one of potential systems. Although there were some studies on FESS, these systems were difficult to store energy for long time. This reason was that they were equipped with ball bearings which induced higher energy loss, furthermore, that the flywheels were made of alloys leading lower rotation speed with lower storage capacities.

On the other hand, it was revealed that a high-Tc superconductor YBa2Cu3O7-x that had a strong pinning force was used in a magnetic bearing [1] and the energy loss of superconducting magnetic bearings (SMB) has been very small. Also the development of CFRP advanced. In these conditions, it is expected that the SMB can be used for large scale FESS.

The present investigation is conducted for designing and manufacturing a medium-sized 10kWh FESS mounted with a CFRP flywheel of the diameter of 1m in order to verify the rotor dynamics realizing a large-sized 10MWh class FESS with high temperature SMB. The flywheel rotor of this system is supported by two radial AMB and one thrust AMB without SMB to verify the energy loss and the rotor dynamics of the system. The flywheel system is anticipated to store the energy of 10kWh by rotating the flywheel up to 17,200rpm with a synchronous motor by the end of March 2000.

The flywheel rotor of the developed system is supported by AMB without contact to enable stable rotation at higher speed with lower mechanical loss. In order to develop the AMB of extremely low loss, a test rig for testing a low energy loss type AMB applicable to a medium-sized 10kWh FESS is developed in the present investigation. Thus, three types of AMB are tested on the test rig with measuring energy loss.

The present paper reports (1) low energy loss AMB developed, and (2) the medium-sized 10kWh FESS and results of rotation tests.

LOW ENERGY LOSS AMB

Structure of the test rig

Figure 1 shows the low energy loss AMB test rig designed and manufactured, and table 1 summarizes the basic specifications for the test rig. The test rotor is an outer rotor type, and a permanent magnet type synchronous motor is mounted inside the rotor. The whole mass of the rotor is supported by a spherical spiral groove bearing (spherical SGB) situated at the lowest position of the rotor. The radial vibration of the rotor is restricted by two AMB situated one at the top and the other at the bottom. Rotation tests are conducted in a vacuum chamber to reduce effects of windage loss as low as possible.

Tested AMB

The AMB designed and manufactured in the present investigation are, (a) a homopolar AMB, (b) a heteropolar AMB, and (c) a homopolar AMB with a permanent magnet (PM) [2]. These AMB are shown in figure 2. All types of the AMB have structures of laminated magnetic steel sheets of 0.35mm thick (stator side) to reduce eddy current loss induced by the rotating rotor. Similarly, opposing parts on a rotor to the AMB (rotor side) have structures of laminated magnetic steel sheets (containing 6.5% silicon) of 0.1mm thick. Usually, an AMB is required to have a certain amount of continuous bias current, and the energy for the current is not so small as to be neglected. Then, the AMB of the type (c) is designed and manufactured. The type (c) substitutes the PM for the bias flux generated by the bias current. The bias flux generated by the PM can be varied by adjusting gap adjustment screws as shown in figure 2(c).

Results of free running

Each pair of the AMB is mounted on the test rig. The rotor is accelerated to 12,000rpm by a motor, and then, the motor current is cut off to let the rotor to rotate freely (free running) for measuring energy loss. The energy loss of the homopolar AMB and the heteropolar AMB at the bias current of 1.5A is shown in figure 3. Here, the effect of windage loss is subtracted from the measured values according to the following equation [3], [4].

$$P_W = C (1 + 2.3\, t / R)\, \rho^{0.8}\, n^{2.8}\, R^{4.5}\, \mu^{0.2}$$

Here,

P_W	:	windage loss	(kW)
T	:	height	(m)
R	:	outer radius	(m)
ρ	:	density of air	(kg/m^3)
n	:	rotation speed	(rpm)
μ	:	viscosity of air	($10^{-3}\ Ns/m^2$)

The energy loss of the motor and of the spherical SGB is also shown in figure 3. The figure shows that the energy loss of only the homopolar AMB is about 150W (75W per one unit of AMB) with the bias current of 1.5A at 12,000rpm. Similarly, that of only the heteropolar AMB is about 380W (190W per one unit of AMB). This energy loss corresponds to as much as 2.5 times to that of the homopolar AMB.

The energy loss of the homopolar AMB and the heteropolar AMB in case of changing bias current into 1.5A, 1.0A and 0.5A is shown in figure 4. The figure shows that the energy loss gets small as the bias current is small for both AMB, and the changing rate of the homopolar AMB is smaller than that of the heteropolar AMB. Furthermore the energy loss of the homopolar AMB with the bias current of 1.5A is smaller than that of the heteropolar AMB with the bias current of 0.5A.

The results shown above indicate the superiority of the homopolar AMB over heteropolar AMB with respect for attaining low energy loss. An estimated the energy loss of the homopolar AMB on the medium-sized 10kWh FESS at the rated rotation speed (17,200rpm) is about 320W (160W per one unit of AMB).

Figure 5 shows measured the energy loss of the homopolar AMB with PM. The bias flux from the PM is adjusted to be equivalent to that with the bias current of 1.5A. The energy loss of the homopolar AMB with the bias current 1.5A is also shown in figure 5. The figure shows that the energy loss is equivalent to that of the homopolar AMB with the bias current of 1.5A. Thus, the homopolar AMB with PM is found to reduce energy loss equivalent to the bias current, leading to energy saving of a storage system.

MEDIUM-SIZED 10kWh FESS

Structure of 10kWh FESS

Table 2 summarizes the basic specifications for the medium-sized 10kWh FESS. Figure 6 shows structures of the mechanical parts of the apparatus, and figure 7 shows the system diagram.

The main body of the flywheel is made of light weight and high tensile CFRP, and is fixed to a center of an outer rotor with an aluminum hub of handle shape. The rotor is to be driven by a synchronous motor/generator equipped with permanent magnets and mounted on a stationary shaft inside the rotor. The stator of the motor/generator is cooled by cooling water flowing inside the stationary shaft.

Two radial AMB are mounted on the top and bottom ends of the rotor for restricting radial vibration of the rotor (unbalanced vibration and earthquake, etc.) [5]. These AMB are same sized homopolar AMB which were verified superior on the energy loss in the previous chapter. A thrust AMB equipped with permanent magnets is mounted at the top of the rotor for supporting the whole mass of the rotor without contact. This thrust AMB not only supports the mass of the rotor, but also restricts vertical vibration. The whole rotor system is enclosed in a vacuum chamber for reducing windage loss during rotation as low as possible. The rotor can be cooled only by radiation here, thus, two infrared radiation thermometers are mounted for monitoring temperature rises of the CFRP flywheel during rotation. Each one of angular ball bearings and of carbon rings as auxiliary touchdown bearings are equipped at upper and lower ends of the stationary shaft to cope with accidental contacts between the rotor and any stationary parts as to be caused by AMB failure. Another equipment is a location device mounted on the lower part of the rotor to lift the rotor to an active range of the thrust AMB. The rotor mounted on the test apparatus can be rotated to 17,200rpm by a synchronous motor in the vacuum chamber for storing the rated energy of 10kWh.

Results of rotation tests

Figure 8 shows the energy loss measured on the test apparatus. The chamber is evacuated to 10^{-3}torr, and the rotation speed is 8,000rpm. The figure also contains the energy loss induced by the motor/generator. The figure indicates that the total energy loss is about 280W. The estimated loss at 17,200rpm based on the measured energy loss is about 700W. Here, the energy loss resulting from only the radial AMB is about 400W (including the thrust AMB energy loss of about 18W, and windage loss of about 10W). This value is larger than the estimated value mentioned in the previous section based on the measured value at low energy loss AMB tests (about 320W) by about 25%, although these values could be thought to be almost the same.

CONCLUSIONS

The results obtained in the present investigation are summarized.

1) The energy loss induced by the homopolar AMB and the heteropolar AMB was measured and compared. The energy loss of the homopolar AMB was found to be smaller than that of the heteropolar AMB. The energy loss of both of the homopolar AMB and the heteropolar AMB got small as the bias current was small, and the changing rate of the homopolar AMB was smaller than that of the heteropolar AMB.
2) The energy loss induced by the homopolar AMB and the homopolar AMB with PM was measured and compared. The homopolar AMB with PM was found to be beneficial in reducing energy consumption of the FESS.
3) A medium-sized 10kWh FESS was designed and manufactured. Some test runs were conducted up to 8,000rpm, and the energy loss was measured. The measured energy loss at 8,000rpm was found to be comparable to that obtained on the low energy loss AMB test rig.

Rotation tests on the medium-sized 10kWh FESS of the rated speed of 17,200rpm will be performed. Results thus obtained will be utilized for further reducing the energy loss of FESS.

ACKNOWLEDGMENTS

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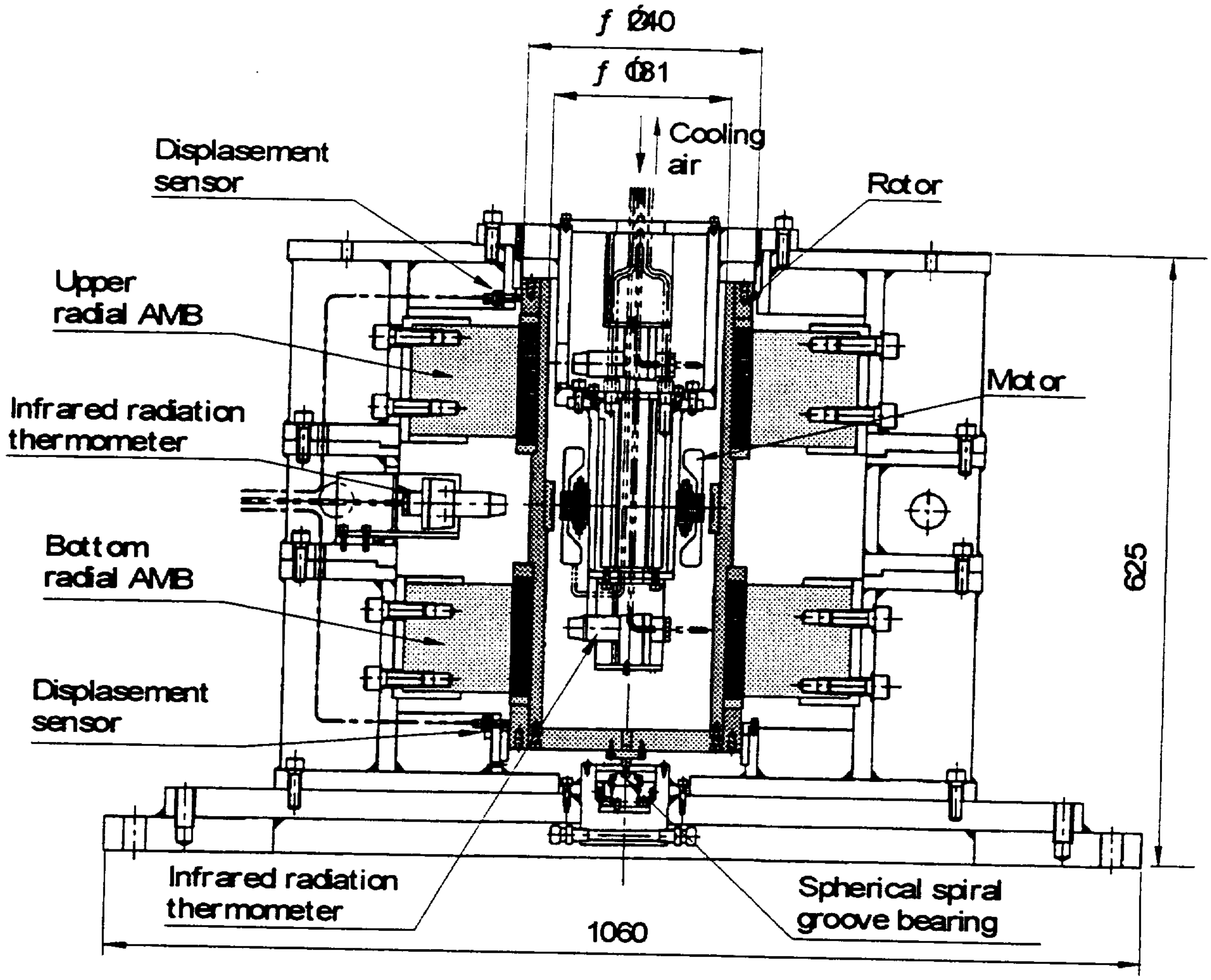
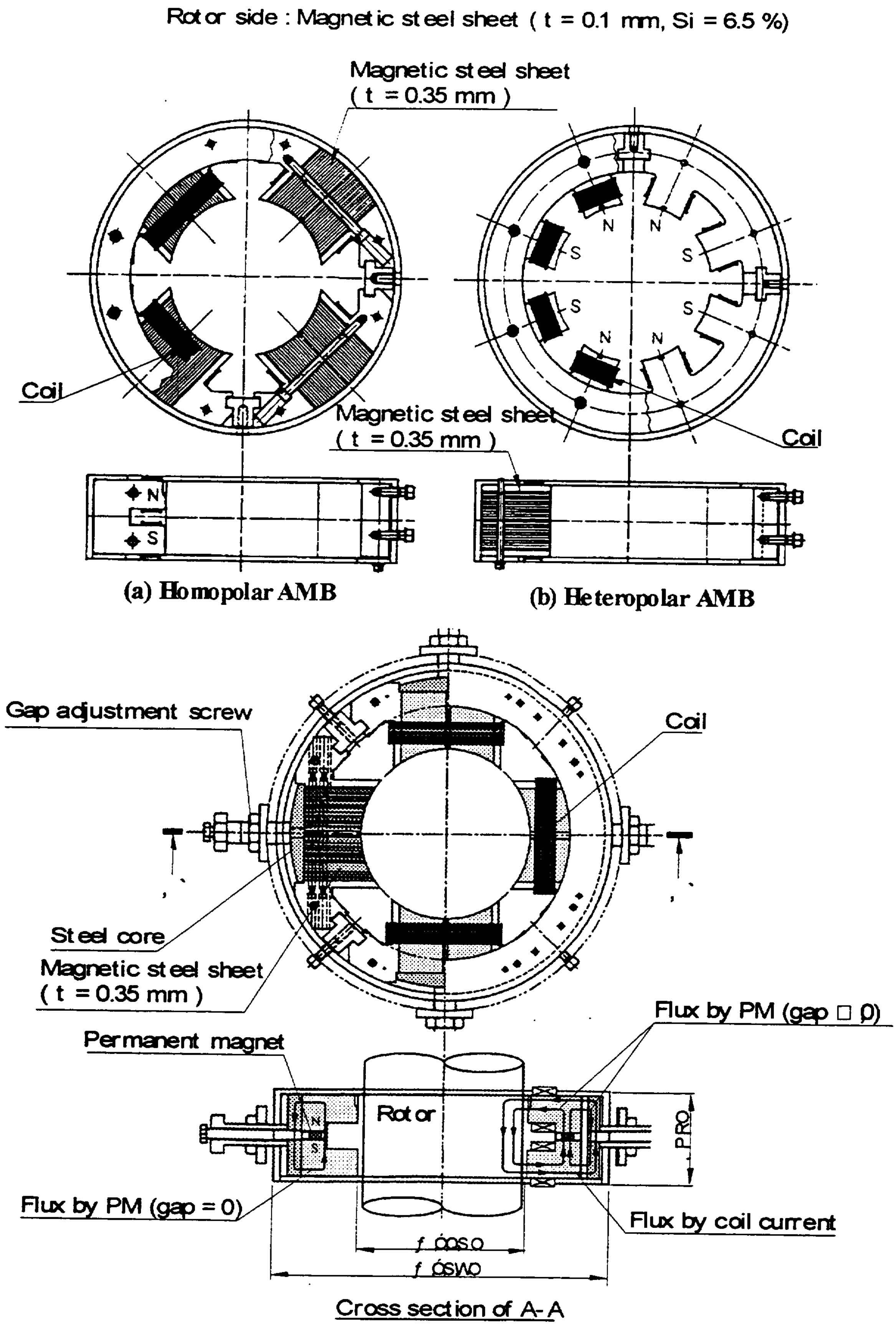


Figure 1. Low energy loss AMB test rig

Table 1. Basic specifications for low energy loss AMB test rig

Max. rotation speed		17,200 rpm (target)
Energy storage		0.34 kWh
Rotor	Inertia	0.75 kgm^2
	Mass	72 kg
	Diameter	ϕ 240 mm
	Length	465 mm
Pressure		Less than 0.1 torr



(c) Homopolar AMB with PM

Figure 2. Tested AMB

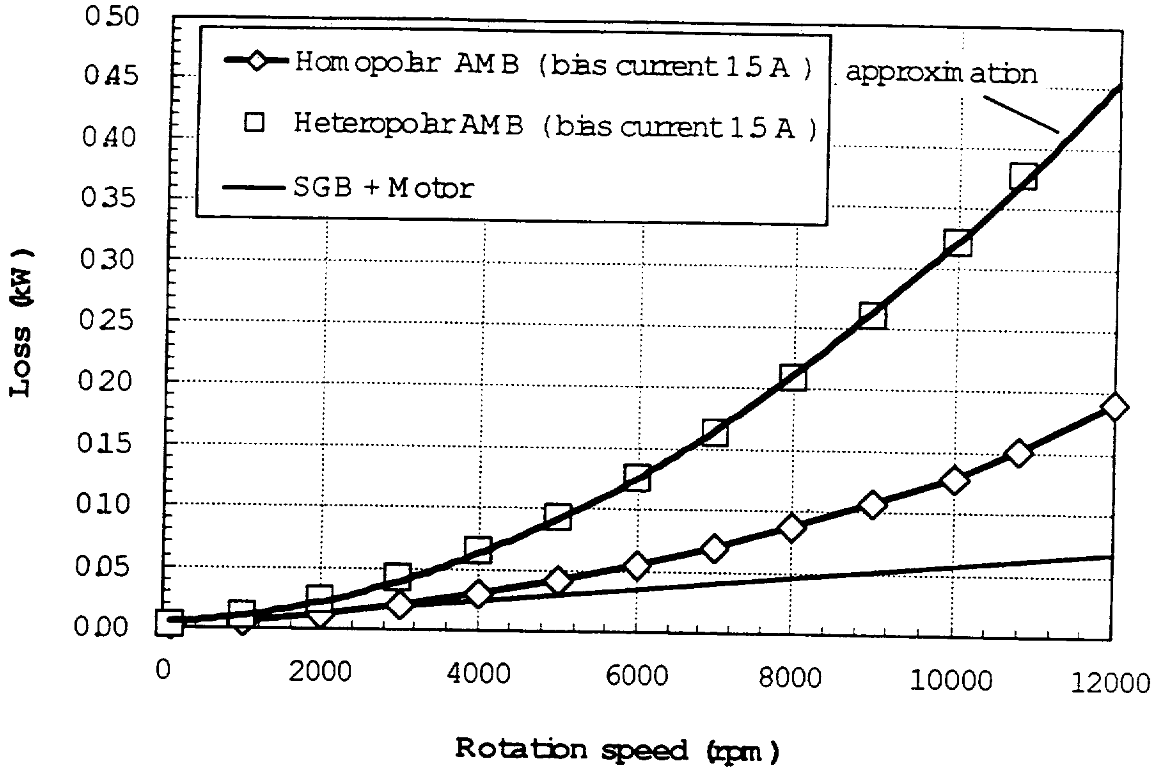


Figure 3. Energy loss of homopolar and heteropolar AMB with the bias current 1.5 A

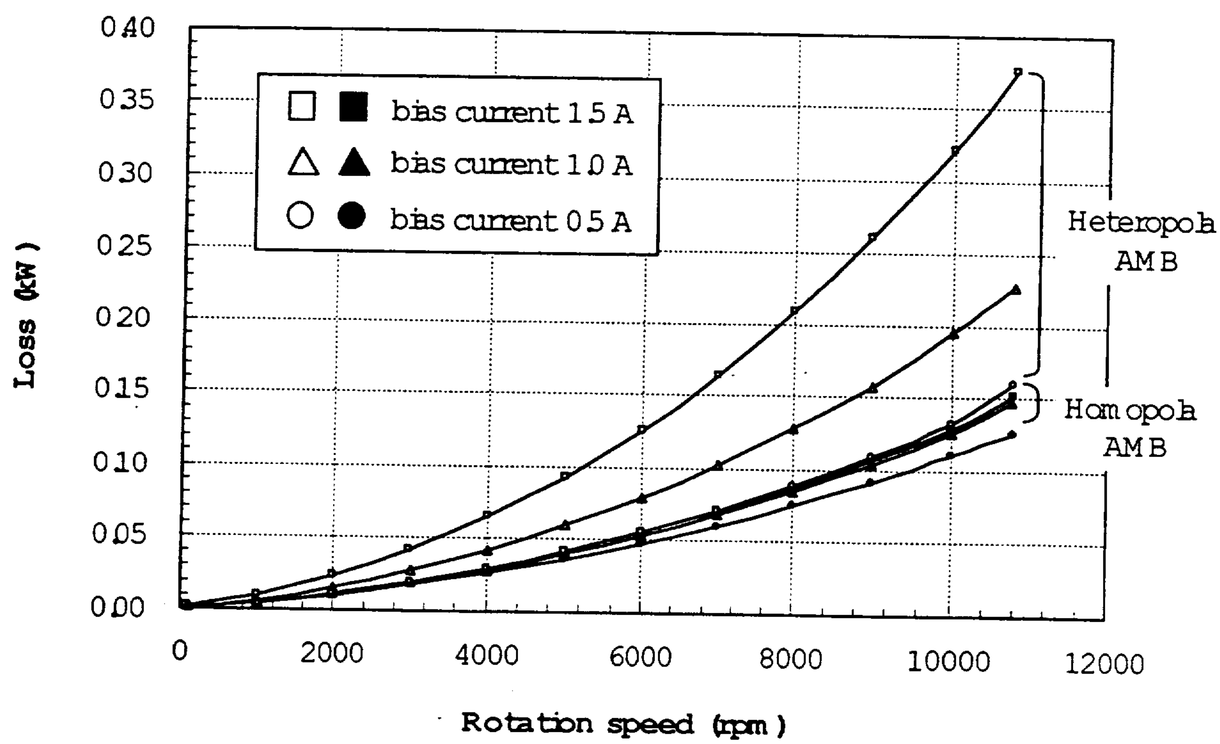


Figure 4. Energy loss of homopolar and heteropolar AMB in case of changing the bias current

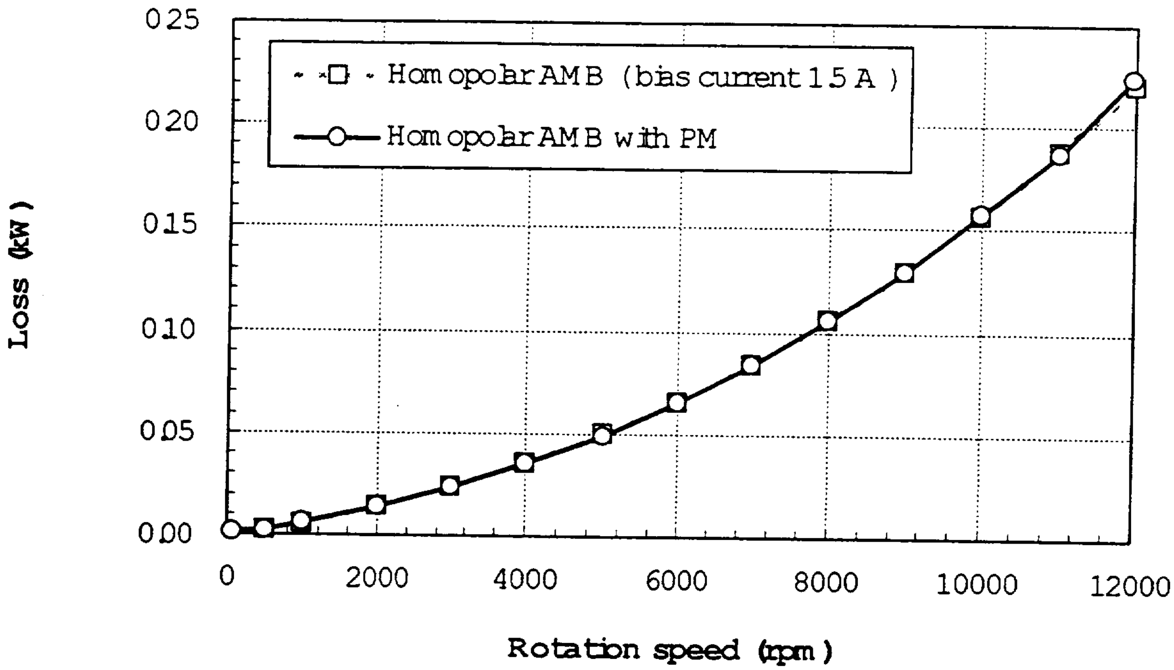


Figure 5. Energy loss of homopolar AMB with PM

Table 2. Basic specifications for the medium-sized 10 kWh FESS

Rotation speed		17,200 rpm (target)
Energy storage		10 kWh
Rotor	Inertia	2.79 x 10^3 kgm^2
	Mass	385 kg flywheel 123 kg rotor 207 kg hub 55 kg
	Length	1040 mm
Pressure		Less than 1 x 10^{-3} torr

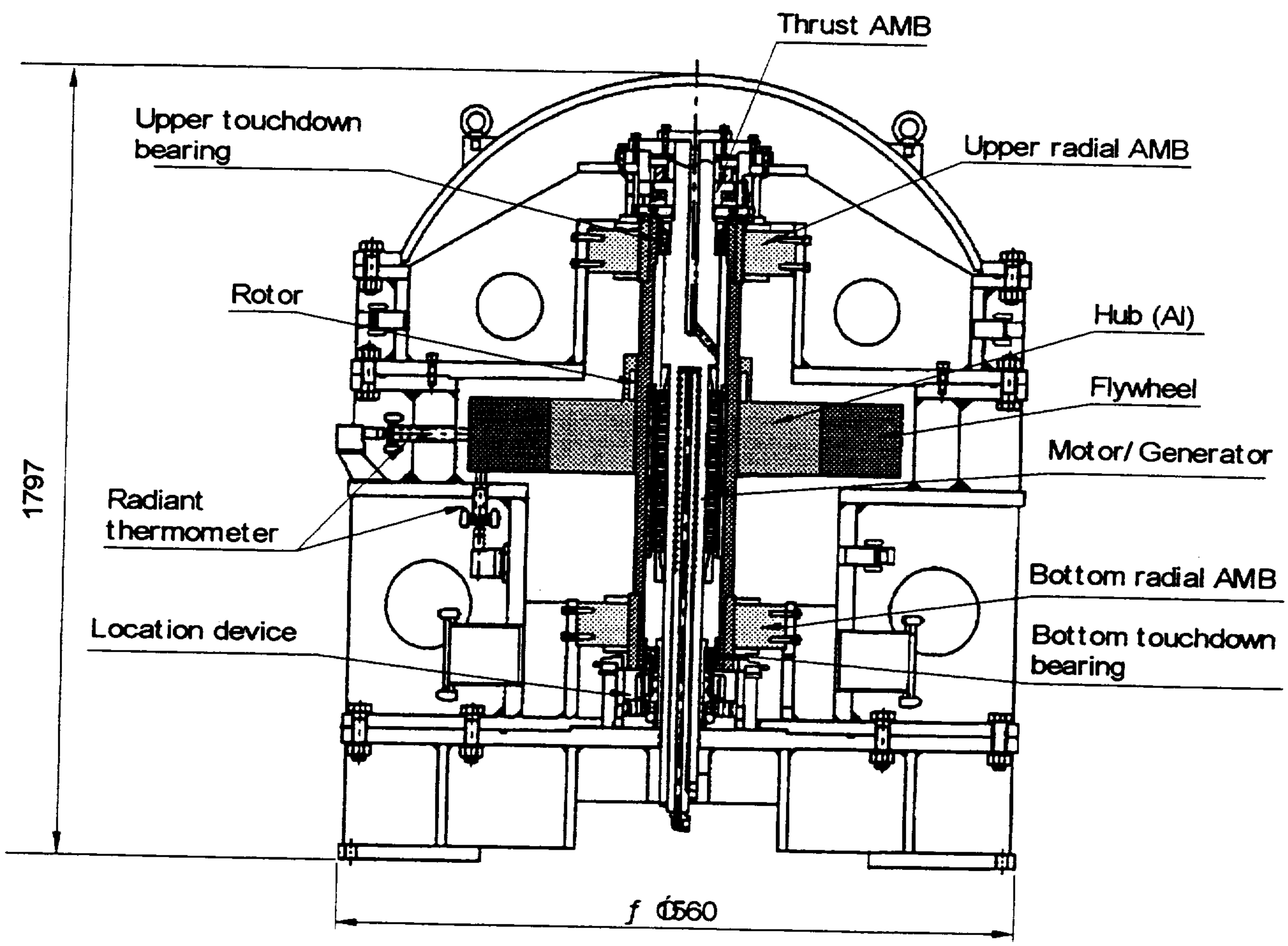


Figure 6. Structure of the medium-sized 10 kWh FESS

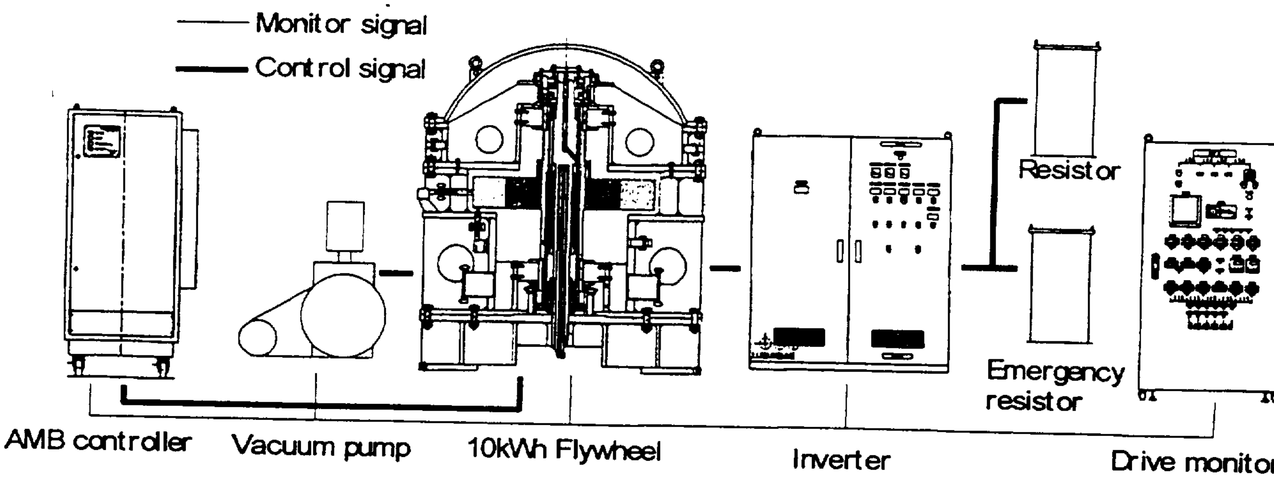


Figure 7. System diagram

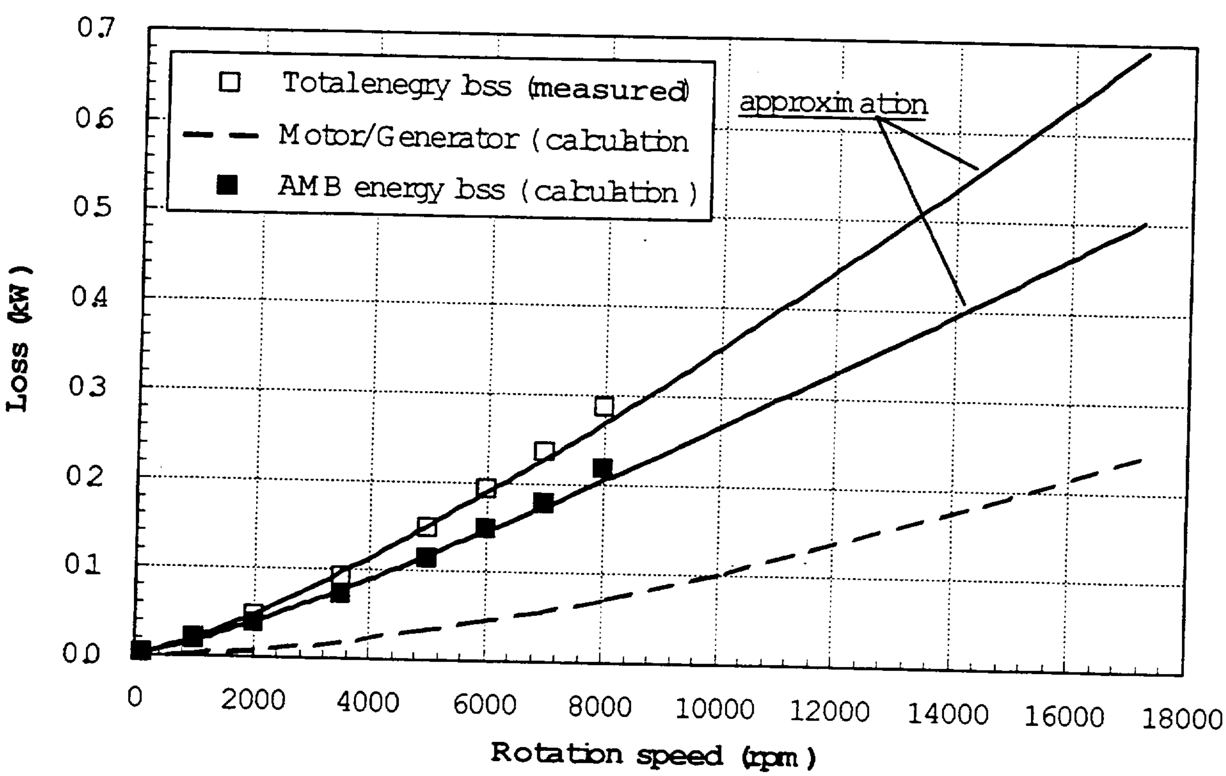


Figure 8. Energy loss measured on the medium-sized 10 kWh FESS