8th International Symposium on Magnetic Bearing
August 26-28, 2002, Mito, Japan

BASIC DESIGN OF 1kWh CLASS FLYWHEEL ENERGY STORAGE SYSTEM

Hironori Kameno
Ryouichi Takahata
Atsushi Kubo
Stefan Gächter
R&D Center, KOYO SEIKO CO., LTD.,Kashihara, Nara-Pref., 634-8555, Japan
hironori_kameno@koyo-seiko.co.jp, ryouichi_takahata@koyo-seiko.co.jp
atsushi_kubo@koyo-seiko.co.jp, stefan_gachter@koyo-seiko.co.jp

Frans J. M. Thoolen
Wilbert G.T. Lommen
Jarno Lathouwers
Centrum voor Constructie en Mechatronica, Nuenen, Netherlands
frans.thoolen@ccm.nl, wilbert.lommen@ccm.nl, jarno.lathouwers@ccm.nl

Kenzo Nonami
Dept. of Electronics and Mechanical Eng., Chiba Univ., Chiba, Chiba-Pref., 263-8522, Japan
nonami@meneth.tm.chiba-u.ac.jp

ABSTRACT
In case of the development of a flywheel energy storage system (FESS) that provides a rated power for several hours, the mechanical and electrical losses of the FESS become a crucial point. Therefore, this article discusses the specifications, in terms of losses, for the active magnetic bearings (AMB), the motor/generator, and the rotor system.
The total loss of a conventional FESS and the methods in order to reduce the losses by almost factor 3.5 are presented. The improvement is mainly due to the reduction of the AMB losses by using nonlinear control. This nonlinear control method avoids the bias currents, which cause considerable rotational losses.
The rotor system's dynamic analysis is done in order to guarantee a stable operation of the FESS in the undercritical range. A security margin of 33.3% results for first bending mode frequency.
The basic design leads to a 1kWh class compact flywheel energy system (ComFESS) that is able to supply the energy of 300W during 3 hours, where the rotational speed decrease from the rated speed of 24,000rpm to a minimal speed of 5,000rpm

INTRODUCTION
Lead batteries are used as backup power supplies of Optical Network Units (ONU) or Remote Terminals (RT) in telecommunication, as shown in Figure 1 [1], or for hybrid power supplies in combination with fuel cells as shown in Figure 2. But, lead batteries have the following problems.

- Lead batteries have a short life time.
- The chemical poisonous substances included in lead batteries can harm people, animals or plants.
- It is necessary to control the temperature around lead batteries.
- Lead batteries need a lot of room.

In order to solve the above problems, the development of a high efficient and clean energy storage system is required to replace lead batteries.

The application area of the flywheel energy storage system (FESS) has been expanded widely by the development of composite flywheels made of carbon fiber reinforced plastic (CFRP) which have high strengths and small weights. Furthermore, FESS is expected as high efficient and clean energy storage system, because FESS has high energy density and high power density [2].

In most of the cases of FESS, which were put to practical use until now, ball bearings were used, because the mechanical and electrical losses are less crucial for application with power demands during several seconds to several minutes. However, for telecommunication applications, loss of the whole FESS becomes a major issue, because power has to be supplied for at least 3 hours in order to guarantee uninterrupted service in case of failure of the power backup system.

In this study, the basic design of a 1kWh class FESS is carried out. This FESS is able to supply power of 300W during 3 hours by rotating CFRP flywheel supported by active magnetic bearings (AMBs) from 24,000rpm to 5,000rpm. Therefore, the goal is the reduction of the losses mainly by applying a nonlinear control method [3] [4] to the AMBs and by redesigning the motor/generator.

In this study, this 1kWh class FESS is called Compact Flywheel Energy Storage System (ComFESS).

TARGET OF LOSS

The design was carried out such that the ComFESS will be able to provide 300W of power during 3 hours.

In order to minimise the dimension of the ComFESS, the diameter of the CFRP flywheel was defined to ø440mm for the outer diameter (the polar moment of inertia is $1.86 kgm^2$).

The rotational decay characteristic of ComFESS with this flywheel was calculated. In this calculation, it was considered to supply driving power for AMB controller and inverter of the generator from ComFESS. The flywheel was slowed down from the rated rotational speed (24,000rpm, 1.6kWh), while consuming 300W of load. The result of this calculation is shown in Figure 3. In this figure, "Conventional" shows the rotational decay characteristic of FESS with conventional AMB and motor/generator. In this result, it was supposed that the control method of AMB was a linear control method with bias current [5] and that the motor/generator design is based on a hysteresis machine with conventional power converter. The result of "Conventional" of Figure 3 delivers only about 1.5 hours in which it is possible to consume the power. Here, the loss of ComFESS at 24,000rpm was classified into the loss of AMB, the windage loss and the loss of motor/generator shown in "Conventional" of Table 1. It is clear that the loss of AMB is the most important.

In this table, "Target" values of the classified losses of ComFESS are also shown. Examinations and considerations will be explained in the following sections.

The "Target" value of windage loss was estimated to be 40W. It is difficult to reduce the windage loss more than this value, because the degree of vacuum was supposed to be about 10Pa. It is not possible to considerably improve this vacuum with standard rotary pumps. Furthermore, the "Target" value of motor/generator loss was estimated to be 80W by assuming minimization of losses by using a new type of hysteresis motor/generator with advanced control strategy for the power converter. The result of "Target" in Figure 3 shows the rotational decay characteristic, when the "Target" values of Table 1 were used. "Target" in Figure 3 shows that it will be possible to consume 300W of power during 3 hours from the initial stored energy.

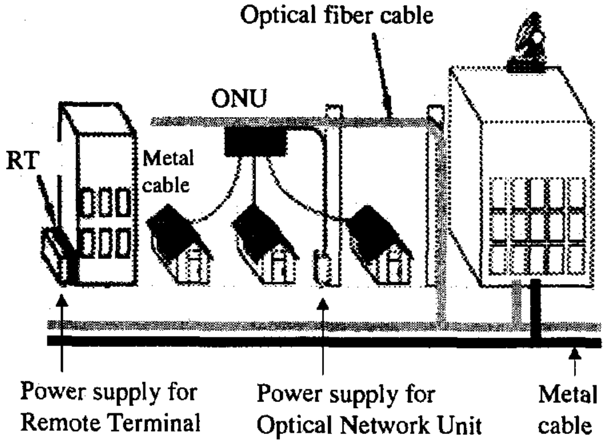

FIGURE 1 : Typical telephone network [1]

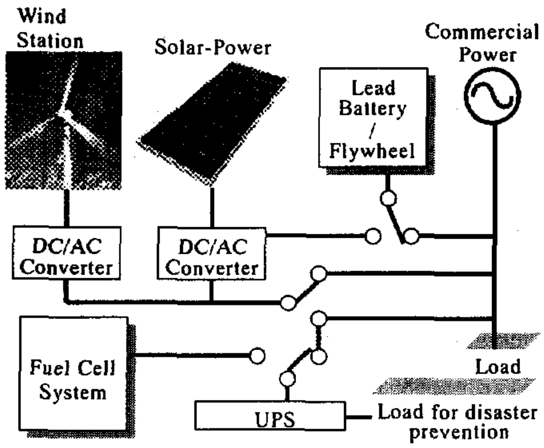

FIGURE 2 : Hybrid power backup system

BASIC DESIGN OF AMB

The loss of AMB of Table 1 was classified as shown in Table 2. In this table, "Conventional" values are based on experimental results [5]. The "Target" values are based on estimated values as discussed in the following sections.

1) The rotational loss of AMBs : This is mainly based on eddy current loss.
2) Consumption of electricity of AMBs : This is based on consumption of current supplied to AMBs.
3) Consumption of electricity of AMB controller: This is based on consumption to drive AMB controller including amplifier of AMB, sensor circuit and so on, excluded bias currents and control currents supplied to AMBs.

In this study, in order to realise the "Target" values of Table 2, the basic design of the axial type active magnetic bearing (AxAMB) and the radial type active magnetic bearings (RaAMB) were examined.

Basic Design Of AxAMB

The mass of the rotor of ComFESS is 75kg. In order to support the weight of the rotor without mechanical support, it is necessary to supply about 4A of lift-up current to the AxAMB (here, the total current supplied to AxAMB = lift-up current + control current). However, this lift-up current increases the consumption of electricity of the AxAMB. Therefore, in order to reduce the consumption of electricity of the AxAMB, the magnetic force generated by lift-up current was replaced with the attracting force of permanent magnets (PM). Figure 4 shows a basic structure of PM biased axial stator (AxStator). The PM biased AxStator has a mechanism to adjust the magnetic flux of PM distributed in the AxStator core by changing PM gap in order to adjust the attracting force of the PM. On the other hand, vibration of the rotor in axial direction has to be damped by the magnetic force generated by the control current. In order to realise PM biased AxStator, it is necessary to supply this control current to strengthen or to weaken the magnetic flux of the PM, and therefore it is necessary to use a bipolar amplifier.

As a result, the estimated consumption of electricity caused by the total current applied to AxAMB becomes almost zero, as shown in (2) AxAMB of Table 2, under the conditions that the rotor is in stable levitation and unexpected vibration does not occur in axial direction during rotation. Therefore, in this study, the "Target" of consumption of electricity of AxAMB was decided to be ≅0W as shown in (2) of Table 2.

It is possible to conclude that the estimated rotational loss of AxAMB is close to zero as shown in (1) AxAMB of Table 2. That is why the changes of the magnetic flux in the circumference direction generated by the control current of AxStator is very small and therefore eddy currents does not occur. Therefore, in this study, the "Target" of rotational loss of AxAMB was decided to be ≅0W as shown in (1) of Table 2.

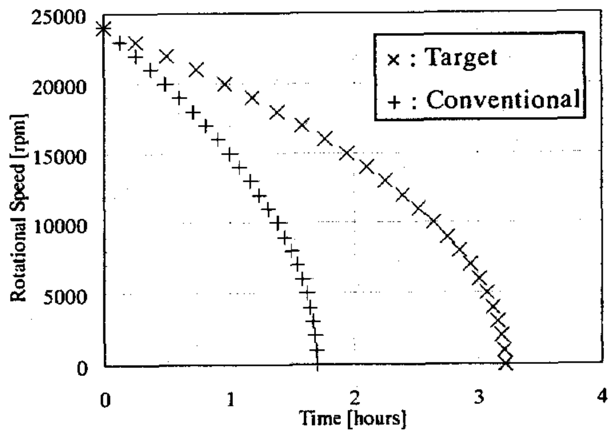

FIGURE 3 : Estimated Rotational Decay of the Rotor

TABLE 1 : Classified Losses of ComFESS @24,000rpm

	Conventional [W]	Target [W]
Loss of AMB	500	100
Windage Loss (at 10Pa)	50	40
Loss of Motor/Generator	200	80
Total	750	220

Basic Design Of RaAMB

For the same reasons as before, it is necessary to reduce the rotational loss and the consumption of electricity of RaAMBs. In this study, a nonlinear control method [3] [4] is applied in order to reduce the consumption of electricity of RaAMB. This control method avoids a bias current, which is the main cause of consumption. As a result, because bias current of RaAMB is suppressed, the consumption of electricity caused by bias currents becomes close to zero, as shown in (2) RaAMB of Table 2, under the conditions that the rotor is in stable levitation and unexpected vibration does not occur in radial direction during rotation. Therefore, in this study, the "Target" of consumption of electricity of RaAMB was decided to be ≅0W as shown in (2) of Table 2.

In case of the application of the nonlinear control method, it is also expected to reduce the rotational loss of RaAMB, because changes in the circumference direction of the magnetic flux generated by the radial stators (RaStators) become smaller and therefore eddy current becomes also smaller. Moreover, we have observed that the rotational loss was largely reduced in other experiments [6], when the RaStators of homo-polar electromagnets and the rotor made of amorphous iron was used instead of hetero-polar electromagnets and rotor lamination made of silicon steel. If the rotational loss of RaAMBs for ComFESS is roughly estimated based on experimental results in [6], the rotational loss is expected to shrink from 200W to 30W, because eddy currents occurred in amorphous iron is reduced. Therefore, in this study, the "Target" of rotational loss of RaAMB was decided to be 30W as shown in (1) of Table 2.

In present stage of this study, hetero-polar electromagnets and rotor lamination made of silicon steel are used. But in future, it is possible to replace this configuration with homo-polar electromagnets and amorphous rotor.

The Consumption Of Electricity Of AMB Controller

Most of the consumption of electricity of the AMB controller is the loss of the DC voltage power supply that is needed in order to drive all electric circuit in the AMB controller. Formerly, a transistor type series regulator that has few noise and low ripple was used for DC voltage power supply. In this case, consumption of electricity of AMB controller was 200W as shown in (3) of Table 2. Recently, in order to reduce that consumption of electricity, high accurate switching regulator with improved noise and ripple characteristics was applied. As a result, the consumption of electricity of AMB controller is expected to reduce to from 200W to 70W as shown in (3) of Table 2. Therefore, in this study, the "Target" of consumption of electricity of AMB controller was decided to be 70W as shown in (3) of Table 2.

TABLE 2 : Loss of AMB @ 24,000rpm

	Conventional [W]	Target [W]
(1)Rotational Loss of AMB	AxAMB : ≅0 RaAMB : 200	≅0 30
(2)Consumption of Electricity of AMB [bias current and control current]	Total : 100	AxAMB: ≅0 RaAMB: ≅0
(3)Consumption of Electricity of AMB Controller [others of (2)]	Total : 200	70

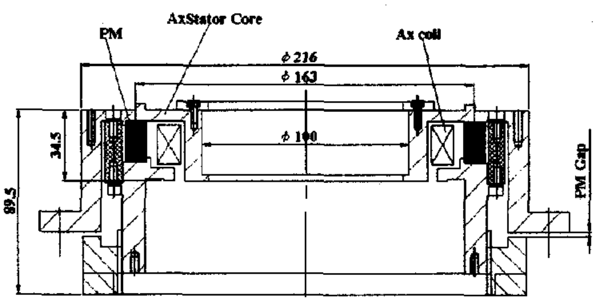

FIGURE 4: PM biased AxStator

Rotor = Main Shaft + Hub + Flywheel + Motor Rotor

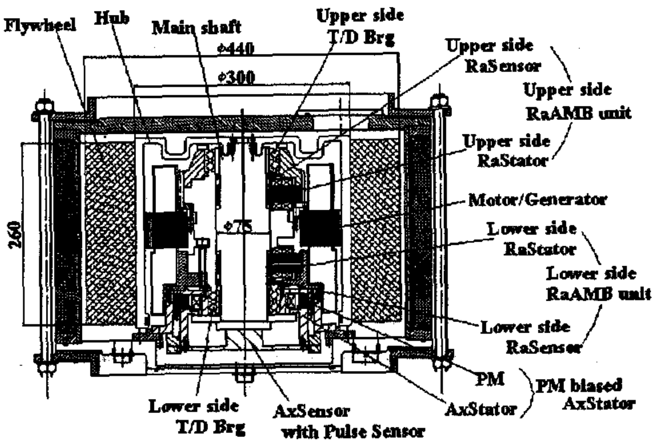

FIGURE 5: Schematic drawing of ComFESS

TABLE 3 : Main Specification of ComFESS

Rotor	
Total Mass of Rotor:	75kg
Main Shaft:	Outer dia. ø 75mm × Length 258mm
Flywheel:	Outer dia. ø 440mm × Inner dia. ø 300mm × Length 260mm
Energy Storage Capacity	900Wh (effective)
Kinetic Energy of the Rotor	1.6kWh (@24,000rpm) 0.1kWh (@5,000rpm)
Power Capacity	300W during 3hours
AxAMB	AMB (1 DOF) PM biased AxAMB
Control method:	Nonlinear control
RaAMB	AMB (4 DOF)
Control method:	Nonlinear control
Electromagnets:	Hetero-polar
Rotor lamination:	Silicon steel plate
Touch Down Bearings	Emergency support for
Upper Side:	Radial direction
Lower Side:	Radial direction and axial direction
AMB Controller	
Power supply for magnets:	80~150DCV ,40A(total)
Max. current for AMB:	8A (max) for each electromagnets
Amplifier :	PWM

ROTOR DYNAMICS OF ROTOR SYSTEM

The mechanical design of ComFESS using the above AxAMB and RaAMBs was carried out. Figure 5 shows a schematic drawing of ComFESS and Table 3 shows the main specification of ComFESS.

In order to stabilise the unexpected vibration of the rotor (=Main Shaft + Hub + Flywheel + Motor Rotor) supported by AMB, it is necessary to increase the bending mode frequencies against the rated rotational speed by optimising the detail structure of the rotor. Therefore, the rotor dynamic analysis of the rotor system as shown in Figure 5 was carried out. As a result, the first bending mode frequency was calculated as 601Hz as shown in Figure 6 and Figure 7. Figure 6 shows the bending mode shape and Figure 7 shows the split of first bending mode frequency against the rotational speed of the rotor. From these results, it is possible to conclude that this rotor system is stable on rated rotational speed (24,000rpm = 400rps), because the security margin of the first bending mode frequency against rated rotational speed is about 33.3% (=(601Hz-400rps)/601Hz).

CONCLUSION

As a result of this study, the following conclusions can be made.

1)It was examined the basic design of the axial active magnetic bearing and the radial active magnetic bearings and the AMB controller. As a result, total value of the loss of AMB is expected to reduce from 500W to 100W.

2)The rotor-dynamic analysis of the rotor system was carried out. As a result, the security margin of the first bending mode frequency against 24,000rpm of rated rotational speed is about 33.3%. This result means that this rotor system of ComFESS is stable on rated rotational speed.

3)As a result of 1) and 2), the basic design of the Compact Flywheel Energy Storage System that is possible to store the energy of 300W during 3 hours is completed.

In near future, the detail design and the manufacturing of ComFESS will be carried out and the above results will be verified.

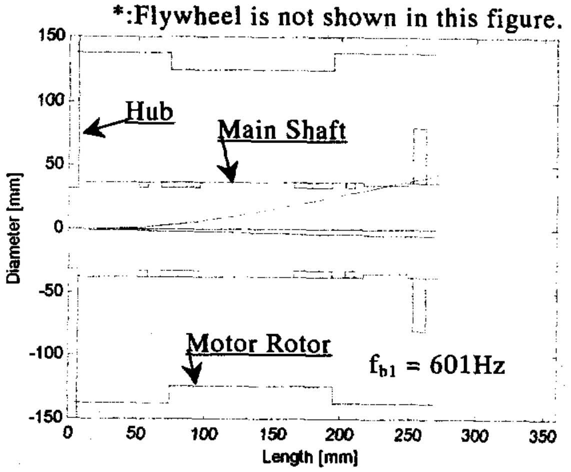

FIGURE 6: Analysis result of first bending mode frequency (f_{b1}=601Hz)

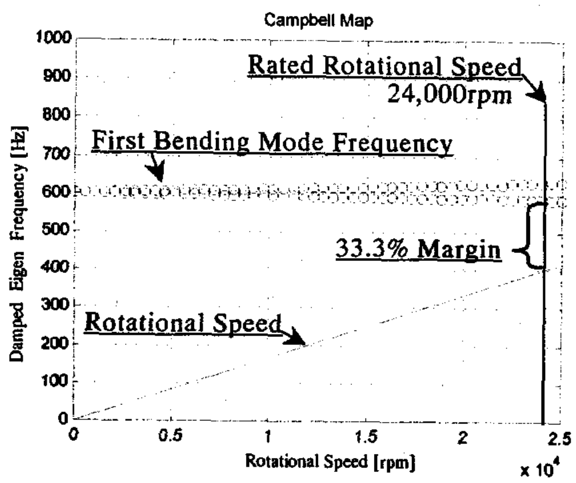

FIGURE 7: Campbell Map of the Rotor

ACKNOWLEDGEMENT

The authors wish to express their gratitude to emeritus professor Schlösser of the Technical University Eindhoven and Mr. Nishimoto of NTRK CO., LTD. for frequent, stimulating and helpful discussions.

This study is supported by NEDO (New Energy and Industrial Technology Development Organization) in Japan, as a part of the NEDO-Grant Project "Compact Flywheel Energy Storage System".

REFERNCES

[1] M.Yamasaki, J.IEEE Japan, Vol. 118, No.9, pp.522-525, 1998, in Japanese

[2] Japan Automobile Research Institute, The Survey on the Energy-Efficient Systems Development: Hybrid Electric Vehicle Systems, JARI Technical Note, No.26, pp.I-69, 1997, in Japanese

[3] Y.Zhang, K.Nonami et al., Zero Power Control of 0.5kWh Class Flywheel System Using Magnetic Bearing with Gyroscopic Effect, Preprint of the Eighth International Symposium on Magnetic Bearings ISMB-8, 2002

[4] S.Sivrioglu, K.Nonami et al., Nonlinear Adaptive Control For a Flywheel Rotor AMB System with Unknown Parameter, Preprint of the Eighth International Symposium on Magnetic Bearings ISMB-8, 2002

[5] Y.Miyagawa et al, A 0.5 kWh Flywheel Energy Storage System using A High-Tc Superconducting Magnetic Bearing, IEEE Transactions on Applied Superconductivity, Vol.9, No.2, pp.996-999, 1999

[6] H.Kameno et al, A Measurement of Rotation Loss Characteristics of High-Tc Superconducting Magnetic Bearings and Active Magnetic Bearings, IEEE Transactions on Applied Superconductivity, Vol.9, No.2, pp.972-975, 1999