Basic Design of 1kWh Class Compact Flywheel Energy Storage System
—Application of Active Magnetic Bearings with Zero-power Nonlinear Control Method—

H. KAMENO  A. KUBO  S. GÄCHTER  R. TAKAHATA

For the development of a 1kWh flywheel energy storage system (FESS) that provides a rated power of 300 W for three hours, mechanical and electrical losses of the FESS become a crucial point. Therefore, this paper presents the specifications in terms of losses for active magnetic bearings (AMB) and motor/generator. The total loss of a conventional FESS and the methods to reduce it almost by a quarter are presented. The improvement is mainly due to the AMB using the zero-power nonlinear control. This control method avoids bias current, which causes the rotational losses and losses in the AMB controller.

Additionally, the dynamic of the rotor, which consists of a shaft and flywheel, is analyzed in order to guarantee stable rotation up to the rated rotational speed. The conclusion is that the unexpected vibration of the rotor caused by bending mode natural frequencies will not occur.

The basic design of the 1kWh class compact flywheel energy storage system (ComFESS), that is able to supply the energy of 300 W for three hours, has been completed.

Key Words: flywheel energy storage system, ComFESS, active magnetic bearing, zero-power nonlinear control

1. Introduction

In the case of an optical fiber communication facility, as shown in Fig. 1, it requires at least three hours of continuous power supply if an accident in the electric power system occurs. Therefore lead batteries are used commonly as a backup power supply to overcome such an emergency situation. However the lead batteries have the problems of:

1. being short life,
2. containing toxic substances,
3. requiring the control of the ambient temperature, and
4. requiring large installation area.

Due to the above reasons, an efficient and clean flywheel energy storage system (FESS), which substitutes the lead batteries, has been expected to be developed.

However, most of the FESS, which have been put into practical application, were developed with the objective of coping with instant power failures or for stabilizing frequencies and thus could supply energy only for few seconds to few minutes. Since the total loss of FESS is not a crucial problem in these applications, ball bearings have been used. On the contrary, in the case in which the FESS is applied as a backup power supply as shown in Fig. 1, which provides power for several hours, the total loss of the FESS is a very crucial problem.

In this study, the total loss was reduced by using active magnetic bearings (AMB), which support a rotor without mechanical contact. Also the basic design of a 1kWh-class FESS which is available to supply 300 W of power continuously for three hours was carried out and the feasibility in terms of losses of this basic design was examined. As a result, the target loss reduction and the subjects to be developed were clarified concerning mechanical components having large losses, and the basic design of the system has been completed.

In this research project, this 1kWh-class FESS is called a compact flywheel energy storage system (ComFESS).

2. Basic Design of ComFESS

2.1 Losses Caused by Using Conventional Technologies

First, the total loss of the ComFESS using a conventional AMB and a conventional motor/generator was clarified. This total loss was classified into AMB loss, windage loss, and motor/generator loss. Each loss was estimated as shown in the "conventional" column in Table 1. Based on the estimated values, the rotational speed decay characteristic of the rotor was computed when the stored energy in the ComFESS was loaded with 300 W. The result is shown in Fig. 2 by the curve composed of "●" marks (conventional values). Therefore, in
the case of using conventional technologies, the rotor stopped (0 min\(^{-1}\)) after about 1.5 hours. This result suggests that each loss when using conventional technologies must be reduced in order to increase the operation time.

For the estimation shown in Fig. 2, it was presumed that the flywheel was made of CFRP (outer diameter was \(\phi\) 440mm and the polar moment of inertia was 1.86 kgm\(^2\)) and that the rated rotational speed of the rotor was 24 000 min\(^{-1}\) (corresponding rotational energy was 1.6 kWh). Furthermore it was considered that the energy stored in the ComFESS is used as a power source for the AMB controller and the inverter of motor/generator.

2. 2 Target Loss Reduction of ComFESS

Next, in order to realize a 1 kWh-class ComFESS, the target loss was set as shown in the "target" column in Table 1, and its feasibility has been clarified.

Table 1 Classification of total loss in ComFESS

<table>
<thead>
<tr>
<th>Loss Category</th>
<th>Conventional</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMB loss, W</td>
<td>500</td>
<td>70</td>
</tr>
<tr>
<td>Windage loss (10 Pa or less), W</td>
<td>50</td>
<td>40</td>
</tr>
<tr>
<td>Motor/generator loss, W</td>
<td>200</td>
<td>80</td>
</tr>
<tr>
<td>Total, W</td>
<td>750</td>
<td>190</td>
</tr>
</tbody>
</table>

Fig. 2 Estimated rotational decay of rotor

If the target values as shown in Table 1 can be achieved, the ComFESS can continuously provide 300 W power for at least three hours. This is shown by "○" marks (target) in Fig. 2. It is expected to achieve the target loss by the following (1) to (3) approaches. Until now the basic design has been completed and from now on, a prototype of the ComFESS will be manufactured and the basic design be validated.

1) AMB loss: PM biased axial AMB and radial AMB with a zero-power non-linear control method are used to reduce the AMB loss from about 500 W to about 70 W (details will be described later).

2) Windage loss: The vacuum degree is assumed to be about 10 Pa and therefore it is difficult to further increase the vacuum degree with a normal rotary pump. Consequently, reduction of the windage loss to the value lower than 40 W is difficult.

3) Motor/generator loss: A hysteresis motor is used to reduce the loss in the motor/generator from about 200 W to about 80 W.

3. Basic Design of AMB

The factors of the AMB loss were further analyzed in order to achieve the target value of AMB loss as discussed in the above section. As a result, AMB losses shown in Table 1 can be classified into the following 1) to 3) specific losses. The "conventional" column in Table 2 shows the values for a conventional AMB.

1) Rotational loss of AMB
   This is mainly caused by the eddy current loss that is generated in the rotor core of RaAMB.

2) Power consumption of AMB
   This is mainly caused by the copper loss caused by the current supplied to the electromagnet.

3) Power consumption of AMB controller
   This is mainly caused by the power consumption for driving the amplifiers, the sensor circuits and others.

In order to achieve the target loss, the basic design of the axial AMB (AxAMB) and the radial AMB (RaAMB) were carried out as described below.

Table 2 Classification of AMB losses

<table>
<thead>
<tr>
<th>Loss Category</th>
<th>Conventional</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) AMB rotational loss</td>
<td>AxAMB</td>
<td>0</td>
</tr>
<tr>
<td>(eddy current loss )</td>
<td>RaAMB</td>
<td>200</td>
</tr>
<tr>
<td>2) AMB power consumption</td>
<td>Total</td>
<td>100</td>
</tr>
<tr>
<td>(copper loss )</td>
<td>AxAMB</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RaAMB</td>
<td></td>
</tr>
<tr>
<td>3) Power consumption of AMB controller</td>
<td>Total</td>
<td>200</td>
</tr>
</tbody>
</table>

Fig. 4 shows the simulated magnetic force of the PM biased AxStator. It is shown in this figure that the PM biased AxStator generates a magnetic force corresponding to...
the rotor weight (75 kg) when the control current is 0 A and that the magnetic force increases or decreases along with the increasing or decreasing control current. It has to be noted that the negative control current shown along the horizontal axis of Fig. 4 means that the control current is supplied in order to weaken the magnetic flux of the PM.

If the rotor achieves stable levitation and rotation, then the control current is almost 0 A. Thus, the copper loss of the AxAMB is almost 0 W as shown in “target” of 2) in Table 2.

Furthermore, the rotational loss of the AxAMB (eddy current loss) is also almost 0 W as shown in “target” of 2) in Table 2. This is due to the fact that the magnetic flux change in the circumferential direction has only a small influence on the rotor and therefore only small eddy current occurs. The same effect was also observed in the case of conventional technologies.

3.2 Basic Design of RaAMB

The current-force relation of each RaAMB electromagnet (RaStator) is nonlinear. (The current \( I_0 \) + the control current \( I_c \) and the force is either \( F_1 \), or \( F_2 \)). However, as shown in Fig. 5, opposing RaStators and using a bias current linearizes the current-force relation (linear control method). The magnetic force acting on the rotor is then \( F = F_1 - F_2 \). Thus, each RaStator must always be supplied with the bias current \( I_0 \). This causes the increase of the power consumption (copper loss) in the RaAMB.

In order to reduce the copper loss, "zero-power non-linear control method" was used. This is the switching control method where only one electromagnet along each direction is active at any given time. This allows having a nonlinear relation between the magnetic forces \( F_1 \) (or \( F_2 \)) and the control current \( I_c \) (or \( I_L \)), as shown in Fig. 6. This method had the problem that the control algorithm was complex. However, recent development in DSP technology provide the needed computing power and thus solved the problem. Furthermore, chattering was also considered to be a problem when the control current was close to 0 A. However this was confirmed to be negligible.

The conclusion is that the zero-power non-linear control method reduces the copper loss of the RaAMB to almost 0 W, as shown in “target” of 2) in Table 2, because bias current is not necessary. However, an additional condition is that the control current too is almost 0 A. This is only the case when the rotor achieves stable levitation and rotation.

Furthermore, the rotational loss of the RaAMB (eddy current loss) is also almost 0 W as shown in “target” of 1) in Table 2. This is due to the fact that the control current is very small and thus a magnetic flux change in the circumferential direction of the RaAMB, and therefore the eddy current in the rotor is also very small.

However, it is predicted that, even in the case where the rotor is in stable levitation and rotation, the driving force of the motor/generator or the unbalance force of the rotor have an influence on the rotor. Therefore small run-out or vibrations are predicted. In such case, the control current to the AxAMB or the RaAMB, in order to reject the disturbance, generates small amounts of copper loss or rotational loss. The design according to this paper has to be further investigated. The authors plan to evaluate, experimentally and theoretically, the amount of this copper loss or rotational loss.

3.3 Power Consumption of AMB Controller

Most of the power consumption of the AMB controller is due to the loss of the amplifier's DC voltage source, the sensor circuit, and the remaining electric circuits in the AMB controller. Conventionally a transistor-type series regulator...
with few noise and ripple was used for the constant voltage power supply. In this case, the power consumption of the AMB controller was 200 W as shown in "conventional" of 3) in Table 2. The recent development of a high-efficient switching regulator has shown the possibility for reducing the power consumption of the AMB controller to about 70 W as shown in "target" of 3) in Table 2.

4. Rotor Dynamics of ComFESS

The mechanical design of the ComFESS using the above-described PM biased AxAMB and the RaAMB with the zero-power non-linear control method was carried out. The structure is shown in Fig. 7. The rotor is composed of the main shaft and the CFRP flywheel which is connected via a hub and bolts to the upper side of the shaft. All components including the rotor, the AxAMB, the RaAMB, and the hysteresis motor are assembled in a vacuum chamber. Main specifications of the ComFESS are shown in Table 3.

Then, the rotor dynamic analysis of the system was carried out. The results are shown in Figs. 8 and 9. Figure 8 shows the 1st bending mode shape. Figure 9 shows the influence of the split of the 1st bending mode natural frequency on the rotational speed.

From these results, it is possible to conclude that the 1st bending mode natural frequency (601 Hz) is sufficiently larger than the rated rotational speed (rotational frequency = 400 Hz) and that unexpected vibration due to the first bending mode at the rated rotational speed will not occur.

5. Conclusion

The research is concluded as follows:
1) The basic designs of the PM biased axial active magnetic bearing, the radial active magnetic bearing with the zero-power non-linear control method, and the AMB controller were carried out. As a result, the AMB loss
reduction from 500 W to 70 W is expected to be achieved.
2) The rotor dynamics analysis of the rotor system of ComFESS was performed. The result of the analysis is that the 1st bending mode natural frequency is sufficiently larger than the rated rotational frequency. Therefore unexpected vibration due to the 1st bending mode of the rotor tends not to appear at the rated rotational speed.
3) The results stated in points 1) and 2) show that the basic design of the compact flywheel energy storage system (ComFESS) that supplies the energy of 300 W continuously for 3 hours is completed.
The authors plan to further investigate the following points in order to clarify the problems for the realization and the practical application of the ComFESS system.
1) Detail design and prototyping of the ComFESS.
2) Theoretical examination of the PM biased axial active magnetic bearing and the radial active magnetic bearing with the zero-power non-linear control method.
3) Levitation and rotational test of the ComFESS.
4) Comprehensive evaluation of the ComFESS.

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