Development of Magnetic Assist System in Flywheel Energy Storage System for Power Load-Leveling

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***Abstract*— This paper presents a flywheel energy storage system (FESS) for load-leveling. In order to improve the efficiency and the lifetime, a permanent magnet synchronous motor, a spherical spiral groove bearing (SSGB) and a magnetic assist system are applied to the prototype. The variable thrust by the proposed magnetic assist system is evaluated. As a result, the variation of thrust becomes 16.4%. In addition, it is observed that the loss of the SSGB relates to the precession movement of the flywheel. Besides, it is observed that the loss of the SSGB depends on the temperature of the lubricating oil.**

Keywords—Energy storage; Flywheel; Magnetic assist

I. Introduction

Renewable energy systems, especially a photovoltaic cell and a wind turbine, generate a power fluctuation depending on the meteorological conditions. Therefore, these systems require energy buffer to suppress the power fluctuations.

Table I depicts the characteristics of each energy storage method. Batteries can achieve a high energy density at low cost. However, one of the problems in the battery energy storage is a short life time. In particular, the lifetime depends on the ambient and the number of charge and discharge time. In addition, the batteries cannot cope with rapid charge and discharge due to a large internal resistance. On the other hand, EDLCs have a high charge and discharge efficiency. Moreover, the rapid charge and discharge are possible because the internal resistance is very small. However, similar to the battery, the lifetime decreases rapidly due to the influence of the ambient temperature [1]. On the other hand, flywheel energy storage systems (FESS) have following advantages compared to chemical batteries: (i) the excellent charge and discharge characteristic with short period, (ii) long lifetime due to no chemical structure, (iii) low maintenance cost, and (iv) environmentally friendly. Therefore, the flywheel has attracted many attentions as an energy storage system [2-8].

TABLE I. Characteristics of energy storage methods.

	Flywheel	Battery	EDLC
Energy storage	Kinetic energy	Chemical reaction	Ion transfer
Charge & Discharge of short period	Fast	Slow	Fast
Temperature characteristic	Excellent	Limited by temperature	Limited by temperature
Energy density	Good	Excellent	Good

In recent years, the flywheel with an ultra-high speed rotation has been studied [2-4]. The kinetic energy which is stored in the flywheel is proportional to the square of the rotational speed. Therefore, the magnetic bearings have been studied in order to achieve high energy density. However, the conventional five-axis magnetic bearing system requires an additional control system [7]. Furthermore, the flexibility of this system is low because this system is necessary to design in accordance with the capacity of the power source to be compensated. On the other hand, in order to increase storage energy, it is necessary to increase the mass of the flywheel in the low-speed-rotation FESS because the kinetic energy is also proportional to the inertia. However, when the typical ball bearing is applied, the bearing loss increases due to the increase in the mass of the flywheel. Therefore, it is more effective to apply a spherical spiral groove bearing (SSGB) as the bearing loss reduction method because the SSGB can float. Furthermore, the SSGB has longer lifetime than the ball bearing [9].

In addition, the magnetic assist system is proposed in order to reduce the bearing loss of the flywheel. Because the flywheel rotates around only one point in the SSGB, the precession movement occurs. This increases the loss of the flywheel. Therefore, the touchdown bearing is employed in order to avoid the precession movement. Consequently, it is necessary to verify the loss of the SSGB using touchdown bearing. Another method to suppress the precession movement is the use of the magnetic assist system which can generate the thrust onto the flywheel. Therefore, the bearing loss characteristic of the SSGB needs to be evaluated in the terms of the thrust of flywheel. Furthermore, the loss in the SSGB is also dependent on the temperature. Therefore, it is also necessary to verify the relationship between the bearing loss and the temperature characteristics of the SSGB, which depends on the weight of the SSGB onto the bearing.

In this paper, in order to improve the efficiency and the lifetime, the PMSM, the SSGB and the proposed magnetic assist system are employed in the prototype FESS. This paper evaluates the proposed magnetic assist system as the first step in order to apply the SSGB. Therefore, the thrust of the proposed magnetic assist system is evaluated by the experiment. In addition, the relationship between the loss and the temperature characteristics in the SSGB is also verified by the experiment.

II. CONSTRUCTION AND STRATEGY OF FLYWHEEL ENERGY STORAGE SYSTEM

Fig. 1 shows the block diagram of the FESS including the measurement system and the auxiliary devices. In the FESS, the PMSM is operated as a generator during acceleration, where the electrical energy is stored as the kinetic energy. On the other hand, during deceleration; the kinetic energy is converted into the electrical energy. Therefore, this system employs a regenerative converter. Furthermore, an overheating of the bearing and the motor can be prevented by the cooling of the oil pump.

Table II shows the specification of the flywheel. It can be observed that the shape of the flywheel is disk-shaped. The stored energy is calculated by (1) from the rotational angular velocity ω and the moment of inertia of the flywheel J.

$$E = \frac{1}{2} J\omega^2 \qquad (1)$$

The flywheel is capable of storing energy up to 0.15 MJ in the prototype to evaluate the fundamental operation. It is noted that the stored energy of the final FESS will be 3 MJ. In addition, the pressure in the vacuum case is reduced by using the vacuum pump in order to further reduce the windage loss. The magnetic coupling is adopted to maintain the vacuum in the vacuum case.

Fig. 2 shows the configuration of the second proposed FESS, the system of the first prototype FESS in which is modified in order to reduce the motor loss and the bearing loss [10]. The low efficiency of the first prototype FESS is caused mainly by the additional loss when the induction motor is used to drive the flywheel. Besides, the PMSM employs the general product due to low production cost. The ratio output of the motor is 3.7 kW. The cause of the mechanical loss comes from the ball bearing. Thus, it is necessary to apply a PMSM and a SSGB to achieve high efficiency for the entire FESS. In addition, SSGB has longer lifetime than the ball bearing. In addition, the flywheel of the second prototype is smaller than that of the first prototype because the purpose of this paper is basic operation verification of the SSGB and the magnetic assist system. The proposed magnetic assist system controls the thrust of the SSGB.

Fig. 3 shows the conceptual diagram of SSGB. The features of SSGB have small friction loss, long lifetime and high reliability. The flywheel axis rotates in the lubricant oil stored inside SSGB. This rotation creates a thin oil sick around the flywheel axis, which makes the flywheel float when rotating. This structure helps the rotation of the flywheel eliminate the mechanical contact with other parts. Consequently, the high efficiency and the abrasion reduction are expected to reduce the cost. In addition, the lighter the flywheel is, the easier it can float. Therefore, the magnetic assist system is proposed in order to reduce the weight of the flywheel.

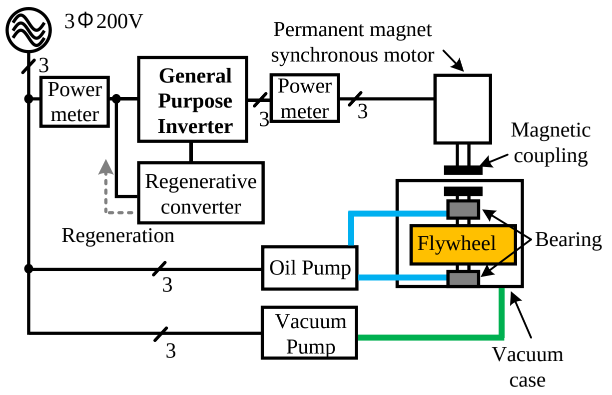


Fig. 1. Block diagram of FESS including measurement system and auxiliary devices.

TABLE II. SPECIFICATIONS OF FLYWHEEL WHICH IS CALCULATED FROM LOW LOSS DESIGN.

Flywheel	Material	SCM440
	Radius	177 mm
	Thickness	65 mm
	Weight of the Flywheel	50 kg
	Stored Energy	0.15 MJ at 6000 r/min
Motor/Generator	MM-BF337 (Mitsubishi Electric)	

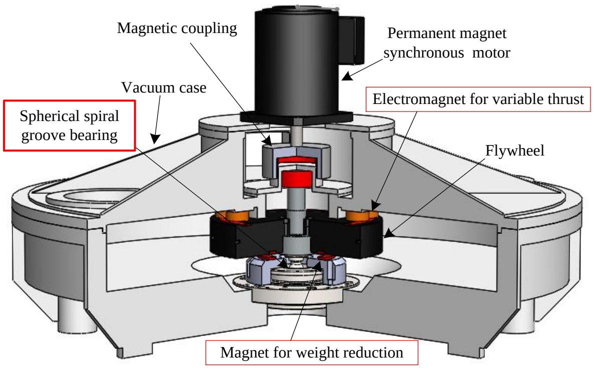


Fig. 2. Configuration of proposed FESS that comprises PMSM, SSGB, and proposed magnetic assist system.

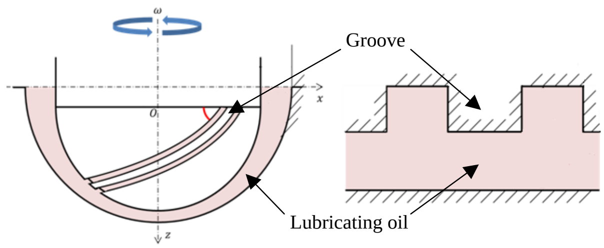


Fig. 3. Conceptual diagram of SSGB.

III. Proposed Magnetic Assist System

The magnetic assist system is considered in this section. The required performances of the magnetic assist system are as follows:

- When the variable thrust structure does not operate, the weight of the flywheel is reduced to approximately 97% by the permanent magnet.
- When the variable thrust structure operates, the maximum variation of the thrust is approximately 10% of the weight of the flywheel.

Fig. 4 shows the designed magnetic assist system. The proposed magnetic assist system consists of the passive type and the active type. There are magnets in bottom of the flywheel and beneath the flywheel in order to reduce the weight of the flywheel by the magnetic repulsion, i.e. the passive type magnetic assist system. On the other hand, the variable thrust structure consists of the electromagnets and the magnet at the top of the flywheel, i.e. the active type magnetic assist system. Note that the coil current is same in all electromagnets. Therefore, 16 electromagnets are operated as one large electromagnet. The current in the electromagnets generates the magnetomotive force (MMF) F, which is obtained by (2).

$$F = NI \tag{2},$$

where N is the turn number of the coil and I is the current. From (2), it is understood that the MMF can be controlled by the current. In addition, the current is controlled by the inverter in order to change the MMF direction. Therefore, the thrust can be controlled indirectly by the current. Then, the thrust characteristic of the designed magnetic coupling is analyzed by the finite element method.

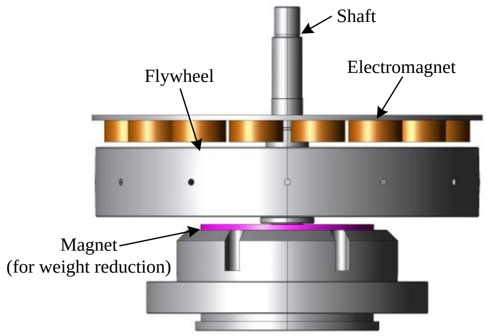
Table III shows the parameters of the designed magnetic assist system. When the variable thrust structure does not operate, the analysis result of the thrust applied to the flywheel is 477 N. In other words, the weight of the flywheel is reduced to 97.3%.

Fig. 5 shows the analysis result of the variable thrust. The variable thrust is 57.5 N (11.7%) at F = 290 A. Therefore, the active type magnetic assist system can be designed as requirement. In addition, the thrust monotonically increases with the MMF. This means that the thrust is controlled easily by the current.

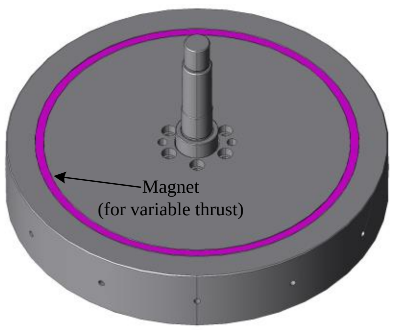
IV. Experimental Results

The variable thrust structure is evaluated with the second prototype. Note that the thrust is not measured directly. In particular, the weight of the flywheel is measured and converted to the thrust.

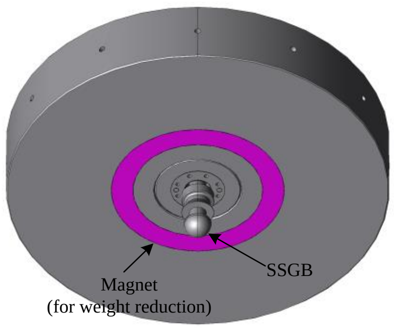
Fig. 6 shows the measurement result of the variable thrust. The variable thrust is 80.2 N (16.4%) at F = 290 A. The measurement result is larger than the analysis result because the analysis model is not perfectly considered as the magnetic materials composing the FESS.



(a) Magnet assist system



(b) Upper side of flywheel



(c) Lower side of flywheel

Fig. 4. Designed magnet assist system. There are the magnets in bottom of the flywheel and under the flywheel in order to reduce the weight of the flywheel by the magnetic repulsion. The variable thrust structure consists of the electromagnets and the magnet in top of the flywheel.

Next, it is necessary to evaluate only the effect of the passive type magnetic assist system for the FESS. In case of only the passive type applied, the oscillation of the flywheel can occurs on the z-axis, because the passive type magnetic assist system can only control the flywheel weight on the z-axis. By using the touchdown bearing, the movement of the shaft of the flywheel on the x-axis and the y-axis can be suppressed. Therefore, it is necessary to evaluate the effects of the use of the touchdown bearing.

TABLE III. PARAMETERS OF MAGNETIC ASSIST SYSTEM.

(a) Magnet for weight reduction

Material	N45M
Thickness	5 mm
Outer diameter	160 mm
Inner diameter	120 mm

(b) Magnet for variable thrust

Material	N45M
Thickness	3 mm
Outer diameter	300 mm
Inner diameter	234 mm

(c) Electromagnet for variable thrust

Material (Core)	S45C
Number of coils	16
Turn number of coil	29

(d) Air gap

Between the magnets for weight reduction	8 mm
Between the electromagnet and the magnet for variable thrust	5 mm

Fig. 7 shows the loss analysis results of the flywheel when the steady rotation speed of the flywheel is 6000 r/min and the pressure of the vacuum case is 3.10 Pa. The mechanical loss of the flywheel without the touchdown bearing becomes 30.4 % higher than that of the flywheel using the touchdown bearing. This is because the precession movement is eliminated when using the touchdown bearing. Therefore, the touchdown bearing of the flywheel is necessary for achieving the low mechanical loss. Nevertheless, when the flywheel uses the touchdown bearing, the mechanical loss of the touchdown bearing still occurs. Consequently, the cancel of the precession movement without the touchdown bearing is necessary in terms of the mechanical loss reduction of the touchdown bearing and also the cost reduction. Therefore, the flywheel using the magnetic assist system is proposed to the high efficiency FESS as a solution for the flywheel without the touchdown bearing. Next, the effect of the active type magnetic assist system is evaluated for the cancel of the precession movement.

Fig. 8 shows the loss analysis results of the flywheel when the rotation speed of the flywheel is 6000 r/min and the pressure of the vacuum case is 3.10 Pa. The weight of the flywheel using the active type magnetic assist system is reduced by 2.92 kg as compared with the weight of the flywheel without using the magnetic assist system. However, the mechanical loss of the flywheel using the active type magnetic assist system is 26.2 % higher than that of the flywheel without using the active type magnetic assist system. As a conclusion, the loss of the flywheel is not improved by the constant thrust of the active type magnetic assist system. One of the reason is that the precession movement changes continuously. Therefore, the precession movement cannot be suppressed by the constant thrust. Besides, the precession movement of the flywheel can be suppressed by designing the center of gravity of the flywheel closer to the SSGB.

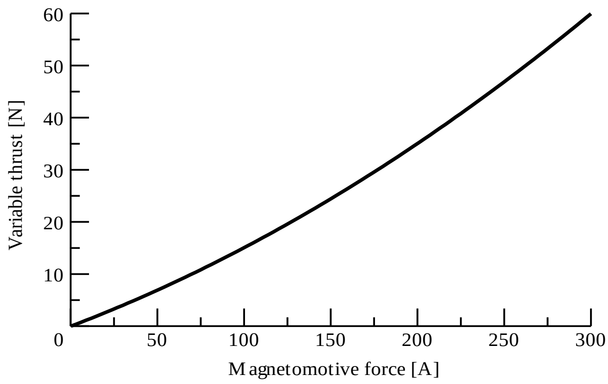


Fig. 5. Analysis result of the variable thrust. The variable thrust is 57.5 N (11.7%) at F = 290 A.

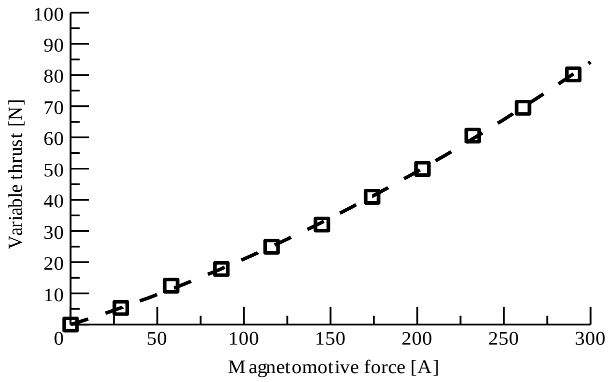


Fig. 6. Measurement result of the variable thrust. The variable thrust is 80.2 N (16.4%) at F = 290 A.

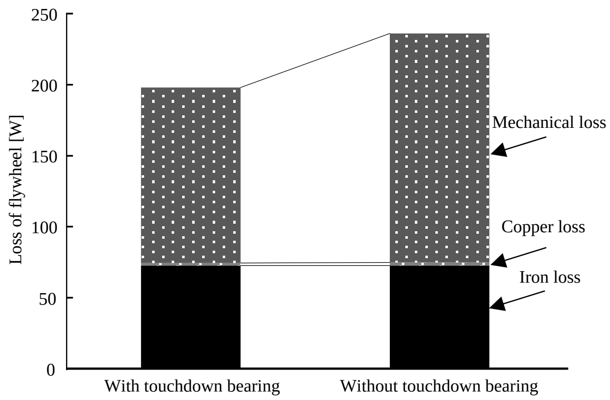


Fig. 7. Analysis result of the loss of flywheel when the steady rotation speed of the flywheel is 6000 r/min and the pressure of the vacuum case is 3.10 Pa. The mechanical loss is increased by 30.4 % without the touchdown bearing.

Therefore, the improvement of the loss reduction due to the magnetic assist system can be expected by adjusting the center of gravity of the flywheel closer to the SSGB.

On the other hand, it is considered the increase in the bearing loss of the SSGB by the constant thrust of the active type magnetic assist system. Therefore, it is necessary to evaluate only the bearing loss characteristic of the SSGB in the case of no precession movement.

Fig. 9 shows the measurement results of the bearing loss characteristic in another prototype of the SSGB for the bearing loss consideration when the rotation speed of the SSGB is 500-4000 r/min. Note that in this prototype, the precession movement is canceled completely, and only the bearing loss of the SSGB is directly measured by a torque meter. The bearing loss increases due to the light weight of the SSGB onto the bearing. In other words, the bearing loss can be reduced by increasing the weight of the SSGB onto the bearing. This is because the bearing loss of the SSGB depends on the viscosity of the lubricating oil.

Fig. 10 shows the measurement results of the temperature characteristic of the SSGB under the same experimental conditions as the measurement results of Fig. 9. The temperature of the lubricating oil increases dependently on the rotation speed of SSGB and the increase of its weight onto the bearing. In addition, the viscosity of the lubricating oil decreases with the increase in its temperature, which leads to the decrease in the fiction between the bearing and the lubricating oil. Consequently, the bearing loss decreases when the weight of the SSGB onto the bearing increases as shown in Fig. 9. However, the decrease in the viscosity of the lubricating oil makes the SSGB difficult to levitate. If the viscosity of the lubricating oil drops below the level when the SSGB cannot levitate, the bearing loss increases notably. As a conclusion, the temperature of the lubricating oil needs to be observed in order to both reduce the bearing loss and make the SSGB levitate.

V. Conclusion

In this paper, the prototype FESS was applied to the PMSM, the SSGB and the magnetic assist system in order to achieve high efficiency and longer lifetime. The prototype was possible to improve the charge and discharge efficiency by applying the PMSM and the SSGB. In addition, the variation of thrust by the proposed magnetic assist system was 16.4%. However, the loss reduction due to the magnetic assist could not be achieved. It was because the complication of the precession movement of the flywheel. The precession movement of the flywheel could be suppressed by bringing the center of gravity of the flywheel closer to the SSGB. Therefore, the improvement of the loss reduction due to the magnetic assist system was expected by adjusting the center of gravity of the flywheel closer to the SSGB. In addition, the precession movement of the flywheel and the temperature of the lubricating oil need to be controlled to reduce the loss of the SSGB.

The future work focuses on the control of the magnetic assist system and the measurement of the charge and discharge efficiency for the prototype FESS. In addition, it is

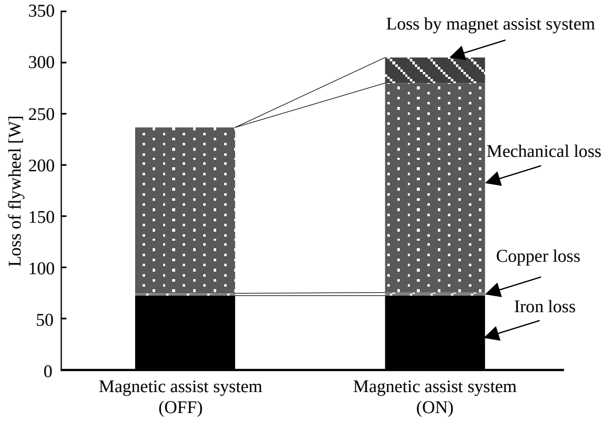


Fig. 8. Analysis result of the loss of flywheel when the steady rotation speed of the flywheel is 6000 r/min and the pressure of the vacuum case is 3.10 Pa. The mechanical loss is increased by 26.2 % by the magnetic assist system.

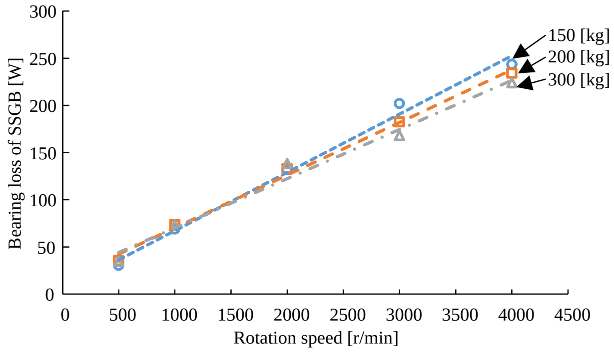


Fig. 9. Measurement result of the bearing loss of the SSGB.

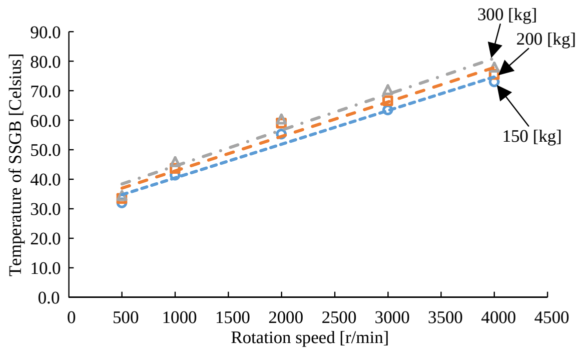


Fig. 10. Measurement result of the temperature characteristic of the SSGB.

necessary to measure the effects of the precession movement and the temperature of the lubricating oil.

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