Flywheel Energy Storage System with Thermal Insulation

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Abstract

This paper proposes a novel design of a magnetically supported flywheel energy storage system with thermal insulation. It utilizes a magnetic coupler to directly transmit the power. The proposed design can induce almost no energy loss. If the power is transmitted indirectly by electromagnetic induction, the energy transmission efficiency will be lower. The motor and the flywheel share the same rotor shaft, and the shaft is supported by two sets of five-degree-of-freedom magnetic bearings. Because the bearings are non-contact, the speed of the flywheel can be increased, thereby the stored energy can be increased. The driving heat source and the heat source of the magnetic bearings are both outside the vacuum chamber of the flywheel, which is easy to dissipate and will not affect the flywheel.

Keywords: *Flywheel Storage Energy System, Magnetic Bearing, Magnetic Coupler*

1. Introduction

Flywheel energy storage system (FESS) with magnetic bearings can realize high speed rotation and store the kinetic energy with high efficiency. Due to its great potential, a large number of research results have been reported in recent years. One critical issue of FESS is the heat dissipation. Since it is in general contained in a vacuum chamber, the heat generated by the motor/generator is difficult to be dissipated. A flywheel with cooling vents was designed in (Song, et al., 2020), where the airflow can be generated when rotating the flywheel. However, the heat from the motor cannot be efficiently removed. In (Qian, et al., 2017), a heat conduction ring and a cooling support are designed to export the heat out of the flywheel chamber. This design will increase the cost, and due to the use of mechanical contact bearings, high speed can hardly be achieved. Some designs separate the drive motor from the flywheel, and use the concept of electromagnetic coupler to drive the flywheel for rotation (Ben, et al., 2017) (Hu, et al., 2019). However, the motor and flywheel are still supported by mechanical bearings. In (Dubois, et al., 2012), the motor is separated from the magnetically supported flywheel, but the motor still supported by the mechanical bearings.

As one can see, to keep the heat source out of the flywheel chamber, the motor is designed outside and the driving torque and power are transmitted through electromagnetic induction. In this way, the motor and flywheel do not share the same rotor shaft and they need to be supported by separate bearings. Contact bearing is the most common choice, but it suffers from the friction problems. An alternative is the magnetic bearing, but the heat dissipation problem in a vacuum environment needs to be resolved.

In this study, the motor and the flywheel are designed to share the same rotor shaft, and the power is transmitted by the magnetic coupler, which is relatively direct and has almost no energy loss problem. If the power is transmitted by electromagnetic induction, there is a problem of energy transmission efficiency. The integrated rotor shaft is supported by a set of five-degree-of-freedom magnetic bearings. Because the bearings are all non-contact, the flywheel speed can be increased, thereby increasing the stored energy. Both the driving heat source and the heat source of the magnetic bearing are outside the vacuum chamber of the flywheel, which is easy to dissipate heat and will not affect the flywheel.

2. System design and modeling

The system under study is shown in Figure 1. The FESS is designed to be 3 KW with the rotational speed of 60,000 rpm. The motor is located on top of the lower flywheel with the same rotor shaft. The rotor of the motor is the outer rotor of the magnetic coupler. The inner rotor of the magnetic coupler is the rotor shaft. Therefore, the motor will drive the magnetic coupler that will drive the rotor shaft and the flywheel. The flywheel (and the whole rotor shaft) is located inside a vacuum chamber so that higher speed can be achieved without the friction loss caused by air. Since the motor and the stator of the magnetic bearings are all placed outside the isolation cover and the vacuum chamber, the heat will not be accumulated within the flywheel system.

The weight of the shaft and flywheel is supported by two sets of passive axial magnetic bearings (upper and lower PMB), where the lower one is placed inside the vacuum chamber. The weight of outer rotor of the magnetic coupler is supported by another two sets of the passive axial magnetic bearings (PMB). All of the passive axial magnetic bearings are designed with Halbach arrays, as shown in Figure 2. In addition, the radial displacement of the shaft and the flywheel is controlled by the upper and lower active magnetic bearings (AMB, as shown in Figure 3) so that the position of the shaft and the flywheel is kept at the center position, as shown in Figure 3. These two sets of AMBs are located outside of the vacuum chamber that are easier for heat dissipation. Finally, the radial motion of the outer rotor of the magnetic coupler is constrained by the ball bearings. Although the friction of the ball bearing will generate heat at high speed, it is outside the vacuum chamber and can be easily removed. It is also possible to replace the ball bearings with AMB, but the dynamics will be very complicated that makes the levitation controller more challenging.

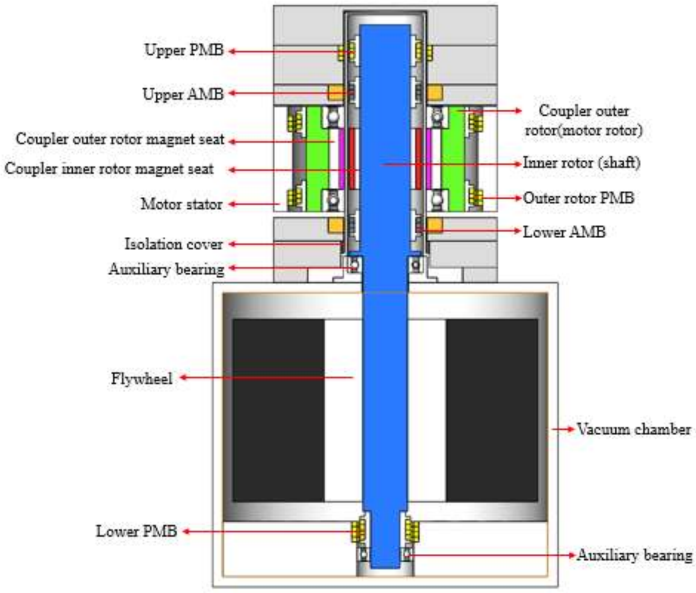

Figure 1 Flywheel system

Figure 2. The axial PMB

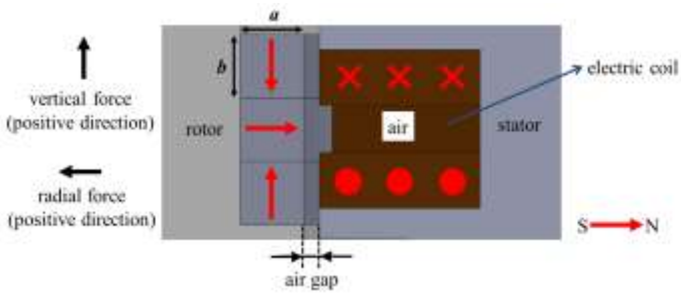

Figure 3. The AMB

Based on the above design, the flywheel system is considered to be 5 degrees of freedom (DOF). The weight of the rotor shaft will be supported by axial passive magnetic bearings and no levitation controller is needed. Also, the axial dynamics of the shaft is decoupled from the radial dynamics and can be neglected. Therefore, only the 4-DOF levitation dynamics in the radial directions will be considered in the mathematical model. When representing the mathematical model of the system, the bearing coordinates of the system are first transformed into the body coordinates of the system. The mathematical model of the system is expressed as

$$M\ddot{q}+G\dot{q}=f \tag{1}$$

where *M* is the inertia matrix consisting of the mass and rotational inertia of the system, *G* is the matrix caused by the gyroscopic effect, $q \in R^4$ is the generalized displacement and $f \in R^4$ is the generalized force from the magnetic force. The generalized force *f* contains several contributions from the PMBs and AMBs, which will be discussed below.

From the experimental identification, the magnetic forces generated by AMBs can be expressed as

$$f_{atx} \approx k_1 i_{tx} \tag{2}$$

$$f_{aty} \approx k_2 i_{ty} \tag{3}$$

$$f_{aby} \approx k_4 i_{by} \tag{4}$$

$$f_{aby} \approx k_4 i_{by} \tag{5}$$

where the subscript *a* represents the active magnetic bearing, *t* is the upper end, *b* is the lower end, $i_{tx,}i_{ty,}i_{bx,}i_{by}$ are the coil currents, and $k_1 \sim k_4$ are constants. It is interesting to note that the magnetic forces generated by the AMB do not depend on the rotor displacements. It depends only on the control currents linearly. This is due to the symmetric coil winding scheme and there is no iron core. As a result, there is no magnetic flux between rotor and stator as long as the coil current is zero, even the rotor position is not zero. Such design makes the levitation controller design easier.

Although the axial dynamics will be neglected and the PMBs are used to provide the supporting axial force direction, the PMBs also generate the forces in the other directions. These forces are assumed to be cancelled out in the radial directions. However, the forces generated by the PMBs can create non-negligible moments for the radial DOFs since the rotor position is not always at the center. In addition to the radial force of the passive magnetic bearing, the axial force also has an effect. The axial force relative to the shaft center also generates a moment that affects the whole dynamics. The forces caused by the passive magnetic bearing are then expressed as

$$f_{ptx} \approx k_5 x_t + k_6 x_b \tag{6}$$

$$f_{pty} \approx k_7 y_t + k_8 y_b \tag{7}$$

$$f_{pbx} \approx k_9 x_t + k_{10} x_b \tag{8}$$

$$f_{pby} \approx k_{11} y_t + k_{12} y_b \tag{9}$$

where *p* denotes the passive magnetic bearing, $x_{t,}y_{t,}x_{b,}y_b$ are the radial rotor displacements, and $k_5 \sim k_{12}$ are constants. According to Newton's law, the equations of motion can be expressed as

$$\sum F_x = m\frac{l_t\ddot{x}_b + l_b\ddot{x}_t}{l_t + l_b} \tag{10}$$

$$\sum F_y = m\frac{l_t\ddot{y}_b + l_b\ddot{y}_t}{l_t + l_b} \tag{11}$$

$$\sum M_x = J_t\frac{\ddot{y}_b - \ddot{y}_t}{l_b + l_t} \tag{12}$$

$$\sum M_y = J_t \frac{\ddot{x}_t - \ddot{x}_b}{l_b + l_t} \tag{13}$$

and

$$\sum F_x = k_1 i_{tx} + k_3 i_{bx} + \left(k_5 + k_9\right) x_t + \left(k_6 + k_{10}\right) x_b \tag{14}$$

$$\sum F_y = k_2 i_{ty} + k_4 i_{by} + \left(k_7 + k_{11}\right) y_t + \left(k_8 + k_{12}\right) y_b \tag{15}$$

$$\sum M_x = k_4 i_{by} l_b - k_2 i_{ty} l_t + k_{13} y_t + k_{14} y_b \tag{16}$$

$$\sum M_y = k_1 i_{tx} l_t - k_3 i_{bx} l_b + k_{15} x_t + k_{16} x_b \tag{17}$$

where l_b and l_t are the lengths from the mass center to the lower and upper ends of the active magnetic bearing, *m* is the mass of the rotor, and J_t is the rotational inertia. With these equations of motion, one can then design the levitation controller for the system.

3. Numerical simulation

The generated magnetic torques and forces are simulated using COMSOL. Figure 5 shows that the torque of the magnetic coupler (shown in Figure 4) if its outer and inner rotors are displaced by some angles. It can be seen that the maximum torque is 33.137Nm. The PMB is used to support the force in the axial direction (weight of the shaft and flywheel), which is around 347.4N. Since there are two sets of PMBs, each set of PMBs needs to support about 170N of force. The magnetic force of PMB is not only related to the magnet, but also related to the air gap and offset. The larger the air gap, the smaller the magnetic force; and the amount of offset is also related to the magnetic force. When the magnet moves up and down vertically, the magnetic force varies.

As shown in Figure 6, when the residual magnetic flux density (B_r) of the magnet is 0.4T, the maximum axial force is below 170N (17kg), so the residual magnetic flux density must be increased. When the magnet residual flux density (B_r) is increased to 1.3T, the magnetic force of 170N corresponds to offset value of about 3.6mm, and when the magnet residual magnetic flux density (B_r) is adjusted to 1.0T, the magnetic force of 170N corresponds to offset of 1.8mm. Therefore, the magnet with a residual magnetic flux density of 1.3 will be selected in the end, because there is a larger space for the rotor to go down, and the operation flexibility is greater.

In Figure 7, when the residual magnetic flux density is 0.45T, the maximum axial force is below 170N (17kg), so the residual magnetic flux density must be increased. Since the lower passive magnetic bearing is a combination of four sets of magnets, although the size is smaller than the upper passive magnetic bearing, the magnetic force corresponding to the increased residual magnetic flux density will be greatly improved, so the residual magnetic flux density is slightly increased to 0.75T, the magnetic force of 170N corresponds to offset of about 2.3mm, which is a value with considerable range for operation as an operating point.

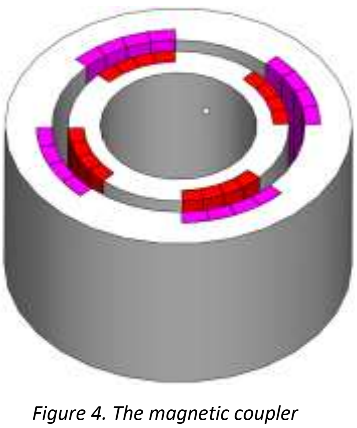

Figure 4. The magnetic coupler

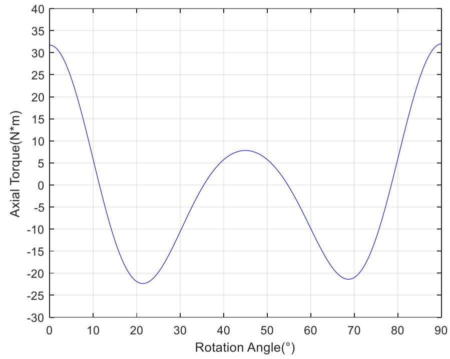

Figure 5. The torque of the magnetic coupler

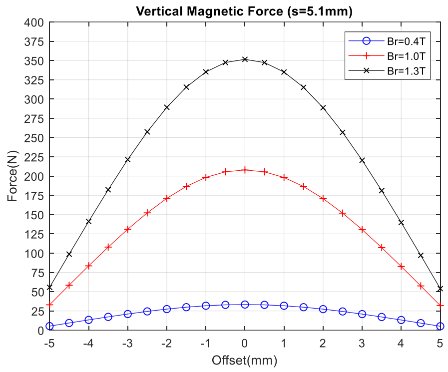

Figure 6 Axial force of upper PMB

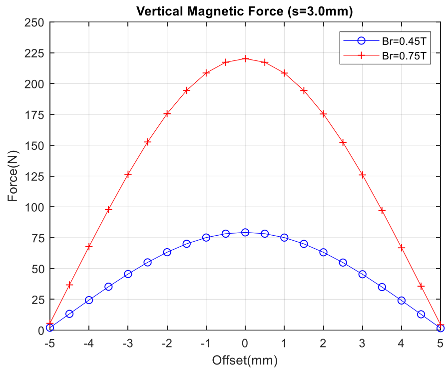

Figure 7 Axial force of lower PMB

4. Conclusions

According to the above simulation, it can be seen that the magnetic coupler can provide large enough torque and the passive magnetic bearing can support the weight of the whole rotor system. In addition, the magnetic coupler method of power transmission is more direct, and there is almost no energy loss problem, while if the electromagnetic induction method of power transmission, there is a problem of energy transmission efficiency.

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