

Modeling and Stabilization of a Novel Flywheel Energy Storage System

Chin-Hsiang Lin*, Shyh-Leh Chen*

* Department of Mechanical Engineering and Advanced Institute of Manufacturing with High-tech Innovations, National Chung Cheng University, Taiwan

sammy8571@yahoo.com.tw / imeslc@ccu.edu.tw

Abstract

This thesis is about a novel design of a flywheel storage system with magnetic bearing. The system employs magnetic coupling technology to directly transmit power. The proposed design results in minimal energy loss. If power is transmitted indirectly via electromagnetic induction, the energy transfer efficiency would be lower. The motor rotor and flywheel share the same rotor shaft, which is supported by two sets of five-degree-of-freedom magnetic bearings. Since the bearings are non-contact, the flywheel's rotational speed can be increased, thereby enhancing the stored energy. The heat sources for the drive and the magnetic bearings are located outside the flywheel's vacuum chamber, facilitating heat dissipation without affecting the flywheel. Additionally, integral sliding mode control (ISMC) has been incorporated. According to simulation results, the system will remain stably suspended at the equilibrium position.

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

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 (H. W. 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 (Z. 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 (Q. C. Hu et al, 2019) (M. Dubois et al, 2012). This study is dedicated to the dynamic modeling and stabilization controller design for this complicated system.

2. System design

The motor is located on top of the lower flywheel. The motor's rotor is the outer rotor of the magnetic coupler. The magnetic bearing, the magnetic coupler and the flywheel share the same rotor shaft. Therefore, the flywheel is driven by the motor indirectly through the magnetic coupler. 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 all of the coil windings (in the motor and the stator of the magnetic bearings) are outside the vacuum chamber, the heat will not be accumulated within the system.

To minimize the heat dissipation, the rotor weight (including the flywheel) is supported by a pair of passive magnetic bearing (PMB) composed of Halbach array of permanent magnets. In addition to supporting the rotor weight, the PMB will also induce moments to the rotor when the rotor is not at the center position. This will cause undesirable tilting rotation motion, and needs to be compensated by the hybrid magnetic bearing (HMB). To this aim, it is desired to express the moments as a function of rotor displacements. Let x_r , x_b , y_r and y_b be the rotor displacements. Let the moments be denoted by M_{xx} and M_{yy} . They are contributed from the 16 sets of passive magnetic units and are given as:

$$M_{vx} \approx \sum_{i=1}^{16} \left[f_{pvri}(z, s_{ii}) \hat{l}_{ii}(s_{ii}) + f_{pvbi}(z, s_{bi}) \hat{l}_{bi}(s_{bi}) \right] \sin \theta_i \approx -k_{myt} y_t - k_{myb} y_b \quad (1)$$

$$M_{vy} \approx -\sum_{i=1}^{16} \left[f_{pvri}(z, s_{ii}) \hat{l}_{ii}(s_{ii}) + f_{pvbi}(z, s_{bi}) \hat{l}_{bi}(s_{bi}) \right] \cos \theta_i \approx k_{mxt} x_t + k_{mxb} x_b \quad (2)$$

which can be modeled as linear functions of the rotor displacements. The details of Eq. (1). and Eq. (2) are omitted for brevity. The radial forces generated by the PMB are also undesirable, and are to be compensated by the HMB. For a given offset (at the operation point), the radial force is a function of the air gap, which is in turn a function of the rotor displacement x_t , x_b , y_t and y_b . One can see that although the radial force is quite nonlinear in the air gap for each magnetic unit, the integrated forces of the PMB in both X and Y directions can be modeled as linear functions of the rotor displacements. In other words, the resultant radial magnetic forces can be modeled as (k_i 's are constants):

$$\begin{aligned} f_{ptx} &\approx \sum_{i=1}^{16} f_{prti} \cos \theta_i \approx k_1 x_t + k_2 x_b, & f_{pty} &\approx \sum_{i=1}^{16} f_{prti} \sin \theta_i \approx k_3 y_t + k_4 y_b, \\ f_{pbx} &\approx \sum_{i=1}^{16} f_{prbi} \cos \theta_i \approx k_5 x_t + k_6 x_b, & f_{pby} &\approx \sum_{i=1}^{16} f_{prbi} \sin \theta_i \approx k_7 y_t + k_8 y_b \end{aligned} \quad (3)$$

The force models of HMB, as functions of rotor displacements and coil currents, are similar to those presented in (Chow Shing and Shyh-Leh, 2016) and are omitted here. With the force models in hand, one can obtain the dynamic model of the system given by

$$M\ddot{q} + K_{ss}q = BK_i i \quad (4)$$

where q represents the rotor displacements.

The FESS system for this study is shown in Fig. 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. All of the passive axial magnetic bearings are designed with Halbach arrays, as shown in Fig. 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 Fig. 3) so that the position of the shaft and the flywheel is kept at the center position, as shown in Fig 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.

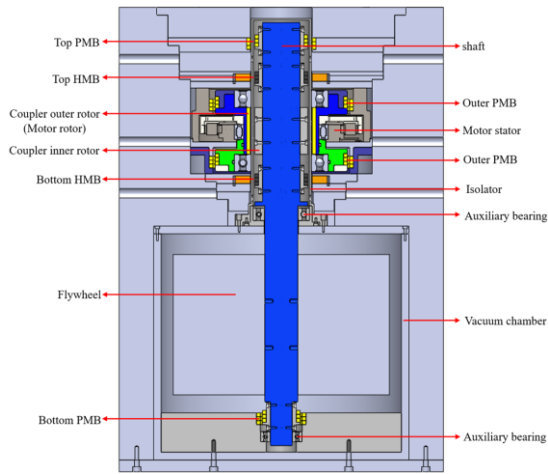


Fig. 1 System design

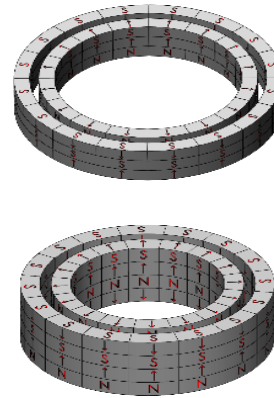


Fig. 2 The axial PMB

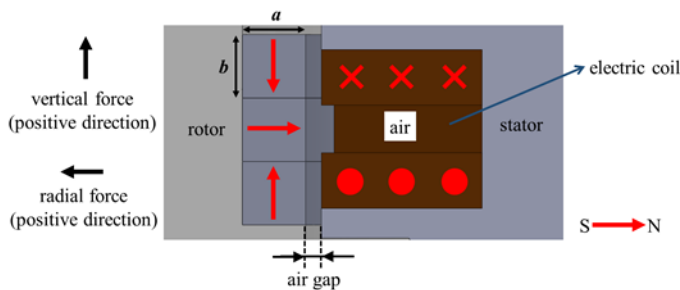


Fig. 3 The AMB

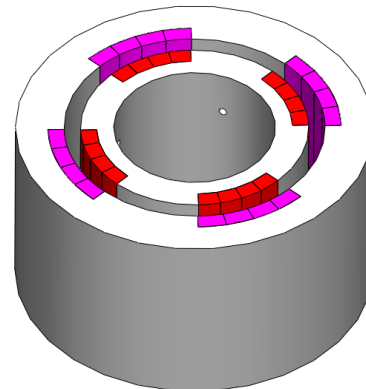


Fig. 4 The magnetic coupler

3. Numerical simulations and controller design

The generated magnetic torques and forces are simulated using COMSOL. Fig. 5 shows that the torque of the magnetic coupler (shown in Fig. 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 380N. Since there are two sets of PMBs, each set of PMBs needs to support about 190N 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.

According to Fig. 6, since the top PMB needs to support a weight of 190 N, the offset is selected as 2.5 mm. According to Fig. 7, since the bottom PMB also needs to support a weight of 190 N, the offset is selected as 2.8 mm.

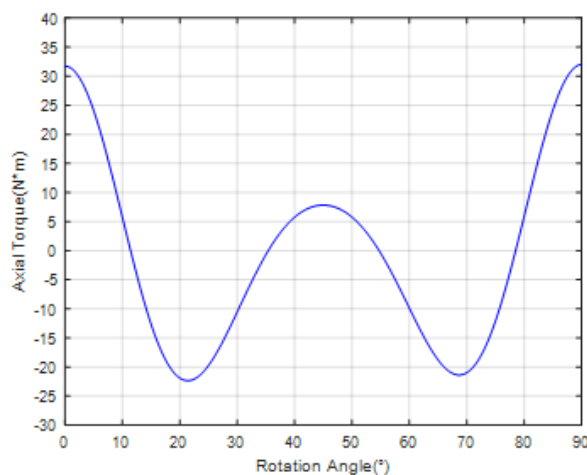


Fig. 5 The torque of the magnetic coupler

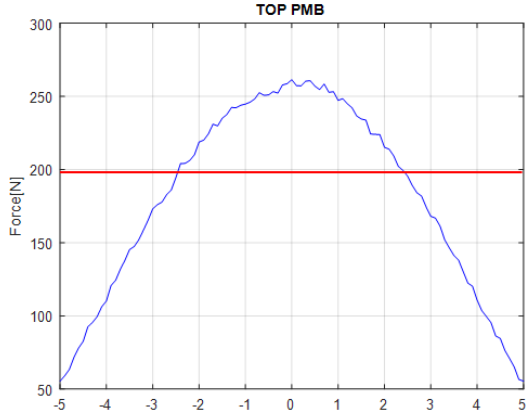


Fig. 6 Axial force of top PMB

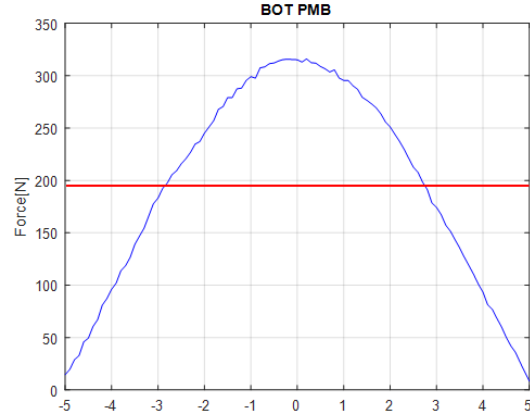


Fig. 7 Axial force of bottom PMB

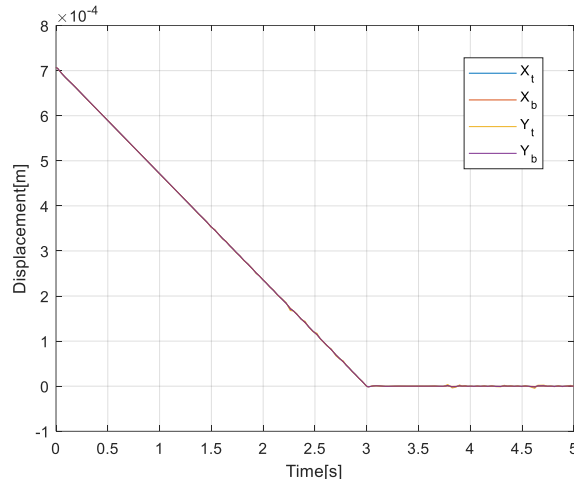


Fig. 8 Axial force of top PMB

Once the mathematical model has been established, the stabilization controller can be designed. Let q_r be the command rotor displacement. Then, the state space model for the tracking errors can be given as

$$\begin{cases} e = q_r - q = \eta \\ \xi = \dot{\eta} = \dot{q}_r - \dot{q} \\ \gamma = \int \eta dt = \int (q_r - q) dt \end{cases} \longrightarrow \begin{cases} \dot{\eta} = \xi \\ \dot{\xi} = \ddot{q}_r - M^{-1}BK_i i + M^{-1}K_{ss} (q_r - \eta) \end{cases} \quad (5)$$

One can design an integral sliding mode controller for the system (5), and the control current can be expressed as

$$i_{eq} + i_s = -\left(M^{-1}BK_i\right)^{-1} \left[\left(\ddot{q}_r + M^{-1}K_{ss}q_r\right) + \left(k_1 - M^{-1}K_{ss}\right)\eta + k_2\xi + k_c \tanh\left(\frac{\sigma}{\varepsilon}\right) \right] \quad (6)$$

The simulation result is shown in Fig. 8. The control parameters in Eq.(6) for simulation are: $k_1 = 16$, $k_2 = 1000$, $k_c = 1$, $\varepsilon = 1000$. The rotor positions follow the commands closely, which reaches the equilibrium position after three seconds from the starting position.

5. Conclusions

The flywheel energy storage system provides an effective solution for renewable energy storage, combining fast charging, long lifecycle and cost-effectiveness. Placing the stator coils of the motor outside the vacuum chamber minimizes heat accumulation in the rotor and maintains component integrity at high rotation speeds. In this work, the dynamic model of the system has been established and controller is designed. Numerical simulations show its feasibility.

References

- H. W. Song, D. L. Ma, Z. Y. Cui, T. Jia and C. Song, "Heat dissipation flywheel and engine assembly," China Patent 210240443U, Apr. 3, 2020.
- Z. Qian, R. Q. Wu and L. Zheng, "Whole heat abstractor of high energy storage flywheel system," China Patent 206807215U, Dec. 26, 2017.
- Q. C. Hu, Q. L. Mai and J. P. Xie, "Flywheel-motor magnetic coupling transmission hybrid power system," China Patent 110365158A, Oct. 22, 2019.
- M. Dubois, M. Desjardins and L. Tremblay, "System for decoupling a rotor from a stator of a permanent motor and flywheel storage system using the same," U.S. Patent 20120176074A1, Jul. 12, 2012.
- Chow Shing Toh and Shyh-Leh Chen, "Design, Modeling, and Control of Magnetic Bearings for a Ring-type Flywheel Energy Storage System," *Energies*, Volume 9, Issue 12: 1051, December 2016.