Operation Test of Magnetic Bearing by Regenerated Power from High-Speed IPM Motor at Unexpected Power Stop

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Abstract

Two pole Internal Permanent Magnet (IPM) type high speed motor has been developed. Hybrid (HB) magnetic bearing is designed and tested by regenerated energy from high speed motor after sudden power stop. The motor should have wide air gap for levitation and the rotor speed is better to be decreased before touch down. The regenerative brake is useful to reduce the rotor speed and to operate the magnetic bearing by the regenerated energy. The motor is designed with a commercial FEM code MagNet. The previously developed magnetic bearing is modified and used to support one end of the rotor shaft and another end is supported by a ball bearing. The motor-bearing system is fabricated and the sudden power stop is tested.

Keywords: *Active magnetic bearing, High-speed motor, Regenerate power, Soft touch-down*

1. Background and Scheme of high speed IPM motor

Scheme of turbo refrigerator is shown in Fig. 1. Turbo compressor increases the pressure and the temperature of coolant efficiently. Pressure is a kind of energy and the standard nozzle expander changes this pressure to increase coolant temperature. Turbo expander cools the coolant efficiently (Mayekawa Mfg. Co. Ltd., Pascal_Air (2022)). This shows one of good application of Active Magnetic Bearing (AMB). However unexpected power stop damages high-speed rotor (Schweitzer, et al., 2009). This paper proposes regenerative brake to IPM type motor and the regenerated power is used to operate the AMB until the rotor speed slows down (Okada, et al., 2019).

Analytical model of the proposed IPM motor and the photo of closed slot stator are shown in Fig. 2. The rotor has 6 internal permanent magnets (Shin-Etsu, N32EZ) to polarize 2 pole N-S rotor, while the stator has 12 slots with 200 sheets of laminated steel (15HX1000). Each stator stems have two layered winding coils. For smooth rotating flux, 24 coils are connected to three phase current amplifiers. The top two coils are connected both to U phase. Then clockwise direction, the next two coils are connected to U and –W. The third two coils are connected both to -W, and the fourth two coils are to -W and V, and so on. The analytical torque versus speed curves are analyzed and compared with 2 pole 6 slot motor. The results are shown in Fig. 3. The 2 pole 6 slot motor shows high torque (Torque2-6), but the top speed is lower (Okada, et al., 2019). The closed slot of 12 slot stator shows high speed rotation (Torqe2-12C), but the produced torque is lower. For this application high speed rotation is necessary, we decided to use the closed slot 12 stator motor, as shown in the right of Fig. 2. Each 24 winding coils are 42 turns with Ø 0.6 copper wire. The inner ends of stator stem are connected with soft magnetic iron with the thickness of 0.7 mm (SUY-1).

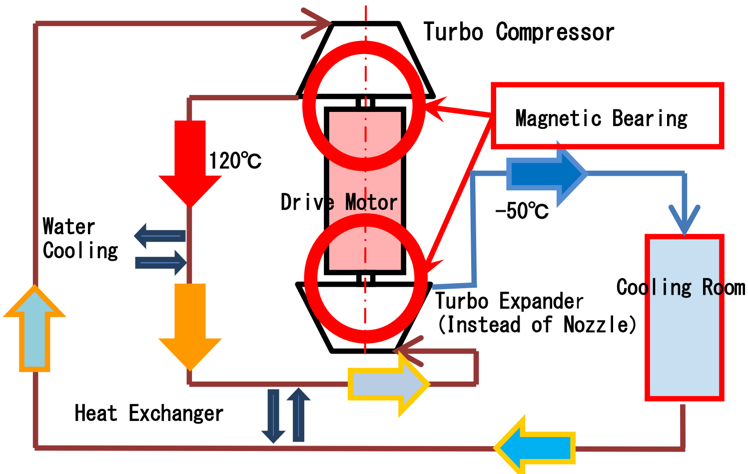

Figure 1 Typical example of using active magnetic bearing to turbo refrigerator.

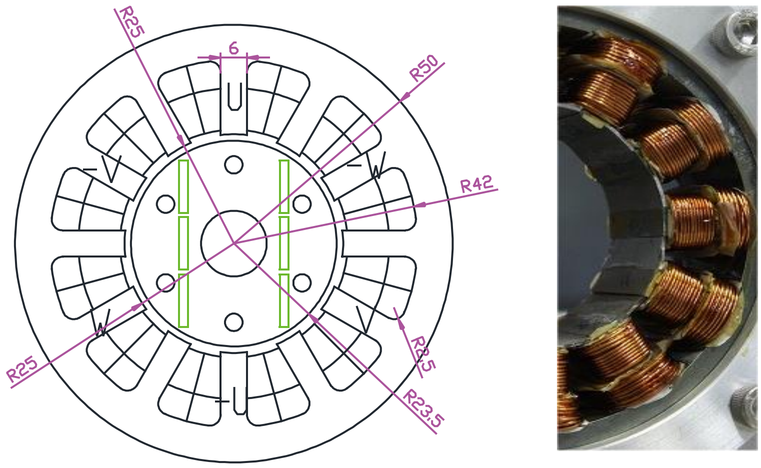

Figure 2 Analytical model of the 2 pole 12 slot IPM motor (left) and the photo of closed slot motor stator (right).

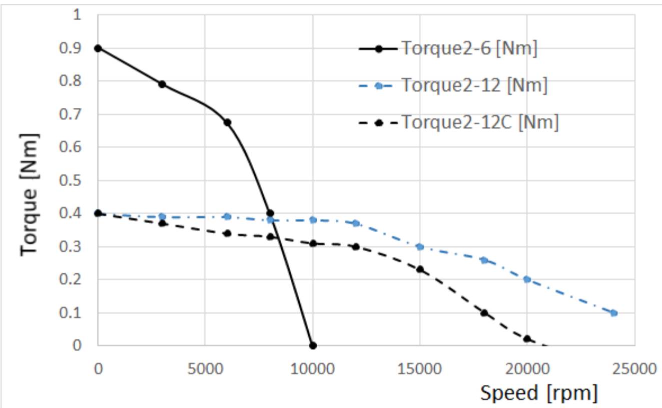

Figure 3 Torque versus speed curves (supply voltage: 72 V).

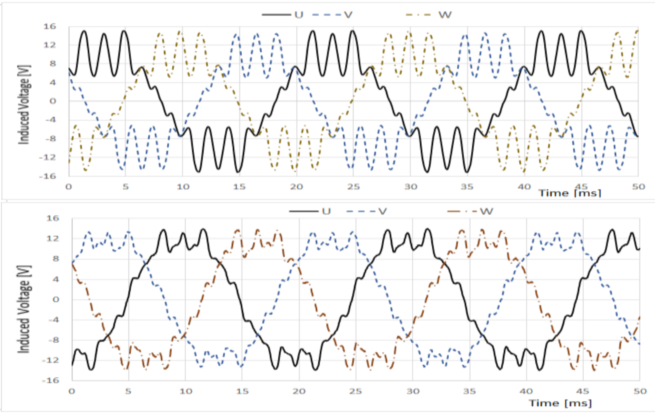

Figure 4 Back electro-motive test results of the motor (upper; open slot, and lower; closed slot ones).

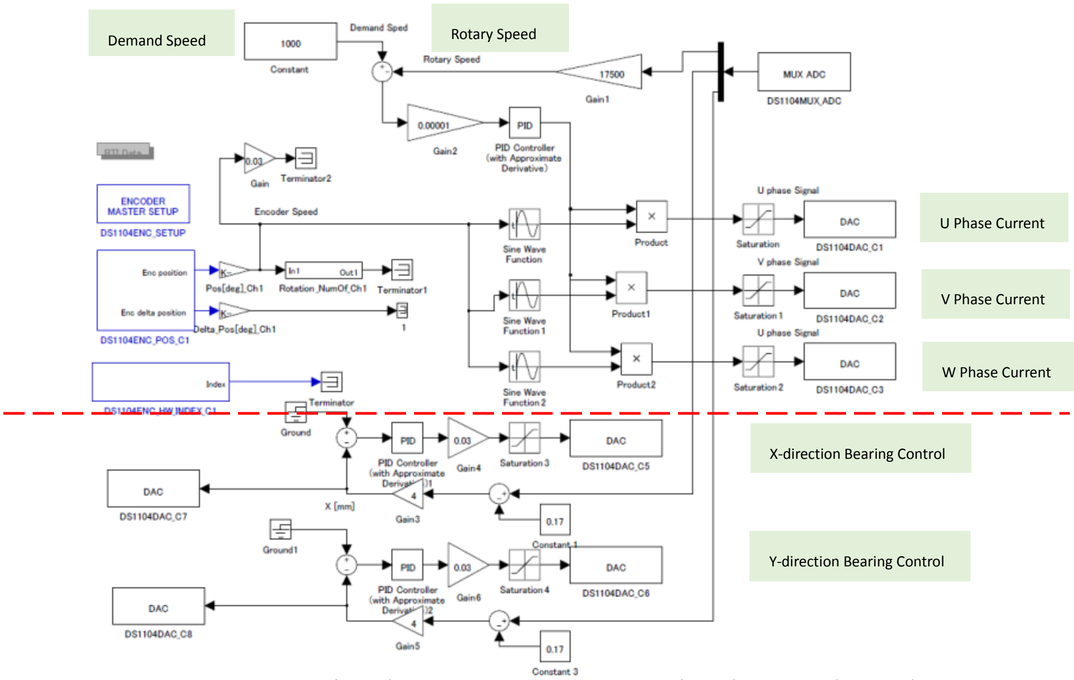

Figure 5 Servo motor controller (upper) and magnetic bearing controller (lower) in dSPACE (DS-1104).

The motor is fabricated and back electro-motive test is carried out at 3,000 rpm with a DC motor (maxon, 148877). The results are shown in Fig. 4. The upper is the result of open slot while the lower is that of closed slot. One can recognize the fundamental rotational wave form. However the closed slot result reduces higher harmonics drastically.

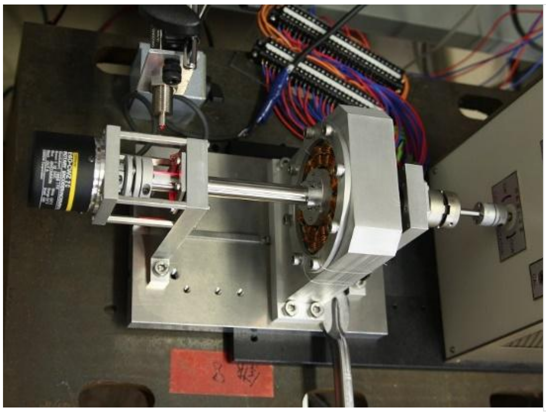

Figure 6 Motor is tested using motor analyzer.

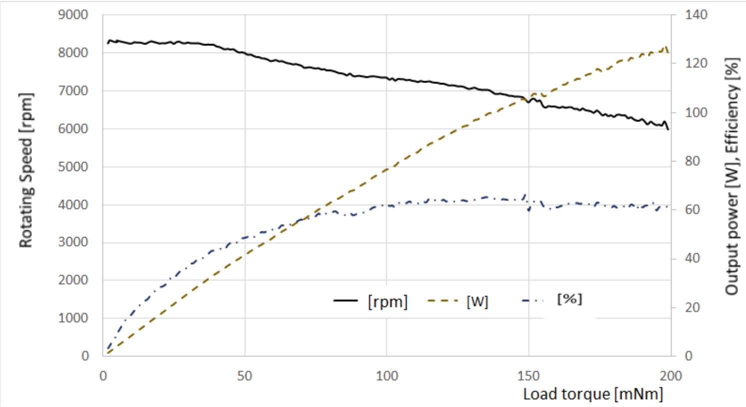

Figure 7 Torque versus speed curves (supply voltage: 72 V).

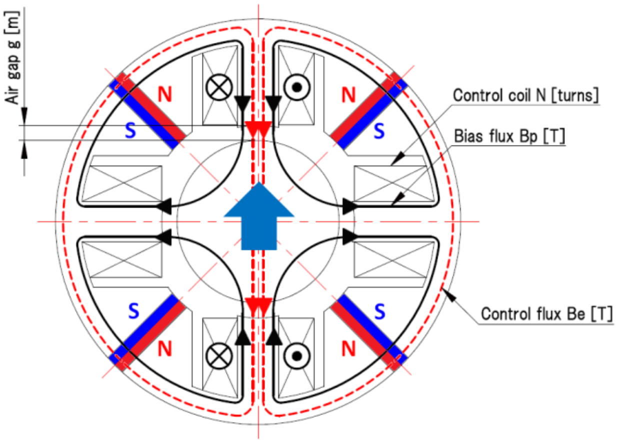

Figure 8 Operating principle of HB type magnetic bearing.

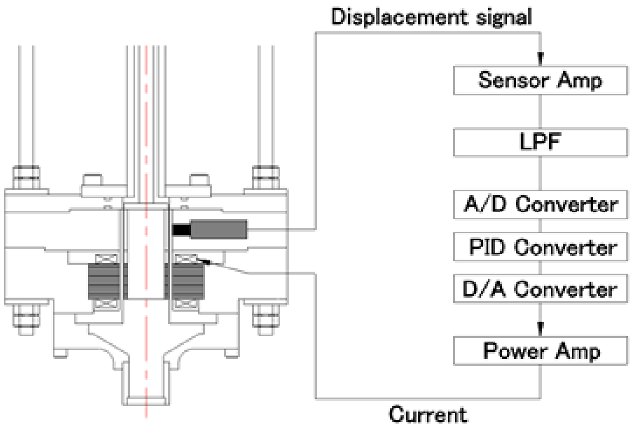

Figure 9 Magnetically supported pump and AMB controller.

2. Experimental setup and control system

Figure 5 shows dSPACE based controller for motor and magnetic bearing. Above the dashed red line is the motor controller, while the lower is the magnetic bearing controller. The motor is controlled by a PID servo motor control using the rotary encoder (E6D-CWZ 2C). The motor can rotate up to 12,000 rpm (Okada, et al., 2021). The turbo refrigerator in Fig. 1 rotates about 18,000 rpm, but in the laboratory test this top speed is considered almost enough.

2.1 Motor load test results

Motor load test is carried out using motor analyzer (Sugawara, PC-SAA2, TB-2KS). Photo of the motor test is shown in Fig. 6. The stable rotating speed with load is little over 8,000 rpm. The motor load test results are shown in Fig. 7. The PID control gains are K_P=2.0, K_I=20, and K_D=0, respectively. The sampling interval used is τ=0.1 ms. The resulting maximum efficiency is about 65 %. The lower efficiency may be due to the wide airgap and shaft is not straight enough.

2.2 Active magnetic bearing and test system

Due to our budget limitation, previously developed magnetic bearing is used to support one end of the rotor shaft and another end is supported by a ball bearing. This magnetic bearing was originally developed to support the liquid nitrogen pump (Okada, et al., 2015). The operating principle is shown in Fig. 8. The scheme of liquid nitrogen pump and the magnetic bearing with controller is shown in Fig. 9. The original designed model of HB magnetic bearing is shown in Fig. 10. The stator has 2 mm thickness cylindrical FRP pipe for separate the liquid nitrogen, hence the magnetic airgap is 3 mm. The bearing part is made by a silicon steel sheet (35A300) with the stack thickness of 30.1 mm. The analyzed flux densities of the control current at 0 A and 2 A are shown in Figs. 11 and 12, respectively. One can recognize the flux of upper stem is increased while the flux of lower stem is decreased by giving control current. The levitation force factor is about 21 N/A as shown in Fig. 13, but the force is not enough. The power amplifier used is analog power amplifier (APEX, PA12A). Hence we modified the rotor part outer radius of magnetic bearing as 1.5 mm larger. The modified design of HB type AMB is shown in Fig. 14. The force factor is about twice bigger and the rotor is levitated stably.

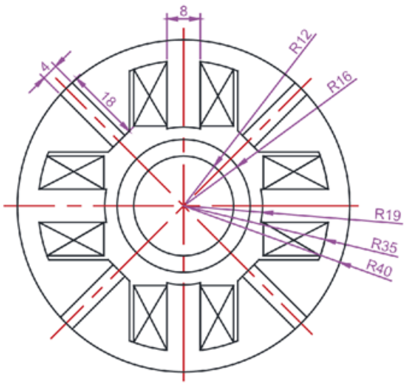

Figure 10 Original design model of HB type magnetic bearing.

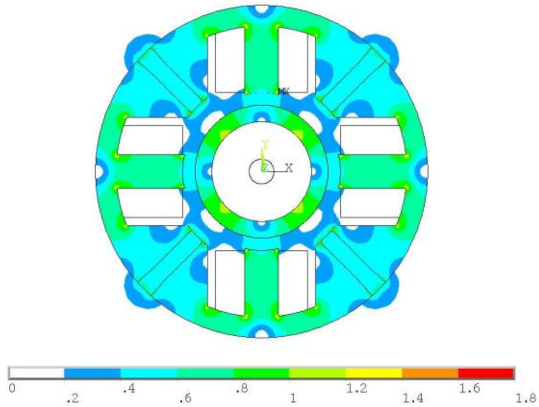

Figure 11 Flux density (Control current: 0 A).

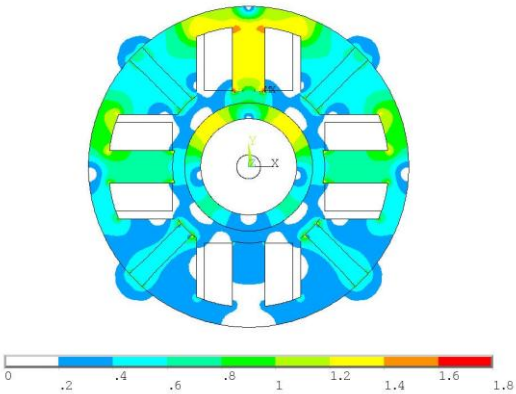

Figure 12 Flux density (Control current: 2 A).

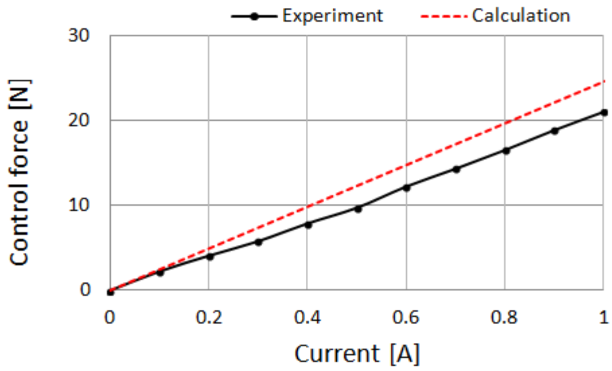

Figure 13 Force property of original magnetic bearing.

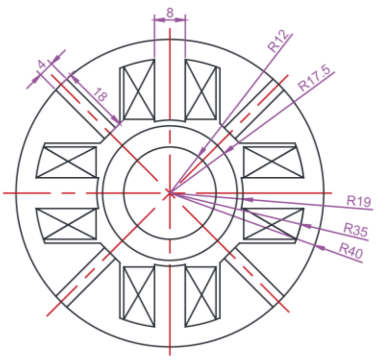

Figure 14 Modified design model of HB type magnetic bearing.

Table 1 Control gains of HB type magnetic bearing.

	Radial Value	
	x -direction	y -direction
K_P [A/m]	300	600
K_I [A · sec/m]	60	60
K_D [A/sec · m]	0.48	12
T_d [ms]	1.667	1.667

2.3 Levitation test of HB type magnetic bearing

The photo of assembled motor with magnetic bearing is shown in Fig. 15. The control parameters of magnetic bearing are shown in Table 1. Where K_p, K_I and K_D are the PID control gains and T_d is the derivative time constant. The step response test is carried out by giving the step signal to x-direction, and then to y-direction. The results are shown in Fig. 16 and Fig.17, respectively. The levitation is stable and mutual interferences are relatively small.

3. Operation test of rotor system at unexpected power stop

During the rotor rotates over 8,000 rpm, unexpected power stop is tested using the rotor system shown in Fig. 15. First, the stable rotation is tested at 12,000 rpm. The driving currents of U, V and W phases are shown in Fig. 18. The motor drivers are PWM amplifiers (Copley Co., model 4212Z), and the current signals are recorded. At the same time, the shaft displacements are measured using eddy current displacement sensors (Keyence, EX-502, EX-008) as shown in Fig. 19. The shaft displacements are under 0.04 mm. The shaft vibration is recognized, but it is relatively stable.

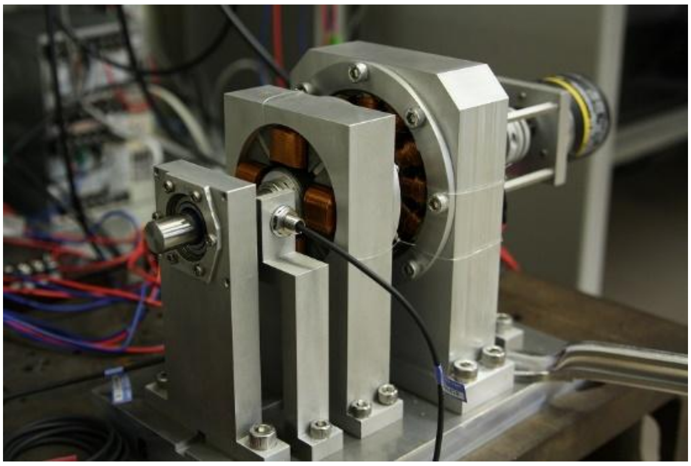

Figure 15 Photo of assembled motor with HB type magnetic bearing.

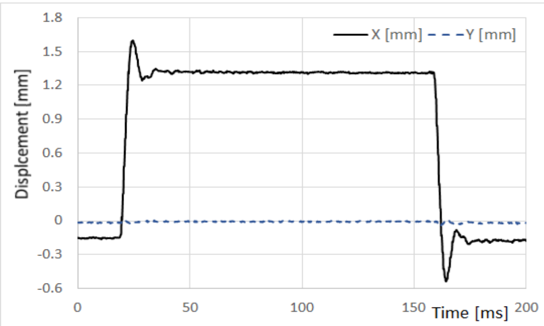

Figure 16 Step response (x-direction excitation).

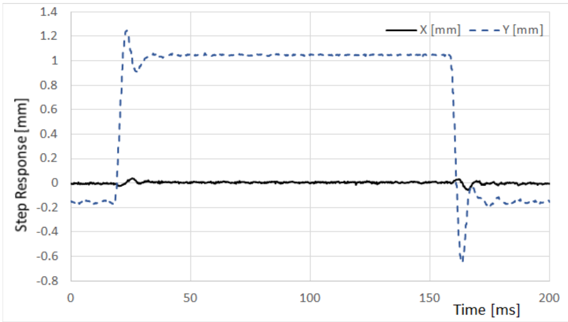

Figure 17 Step response (y-direction excitation).

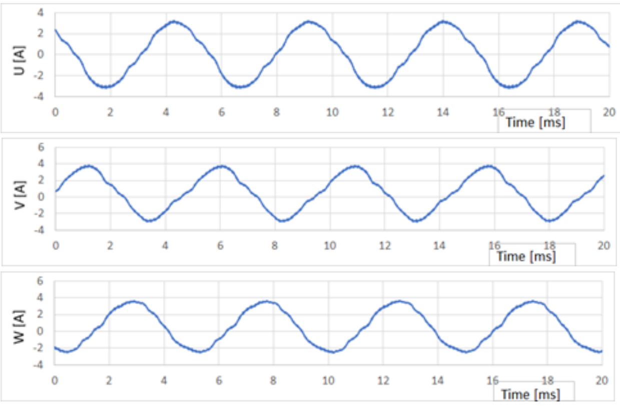

Figure 18 Driving currents of U, V and W phases [A].

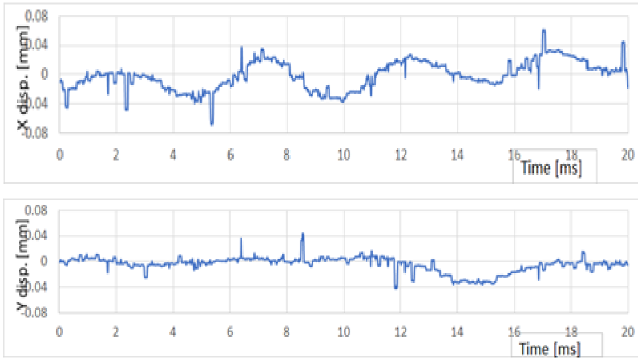

Figure 19 Shaft displacements of x and y directions [mm].

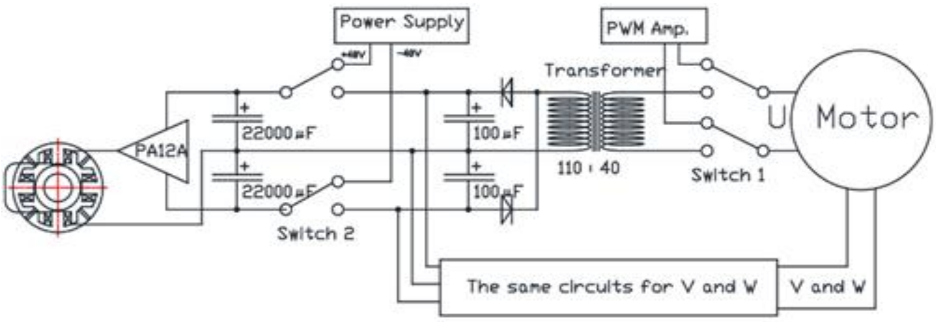

Figure 20 Regenerative circuit from motor to AMB.

3.1 Unexpected power stop

During the motor rotates about 8,000 rpm, unexpected power stop is tested using the regenerative circuit as shown

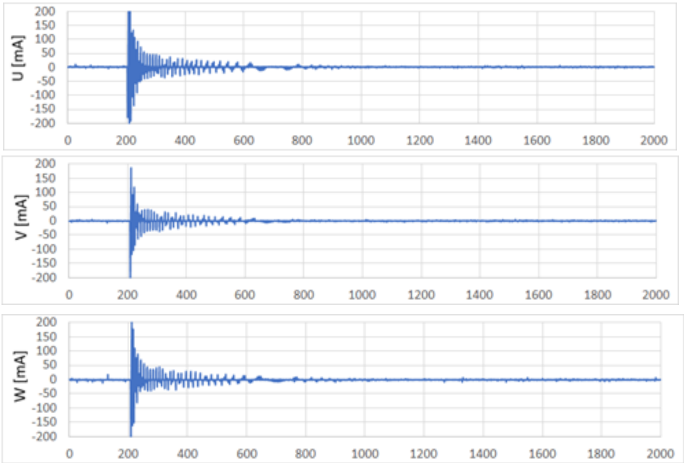

Figure 21 *Regenerated currents of U, V, W phases [mA] versus time [ms].*

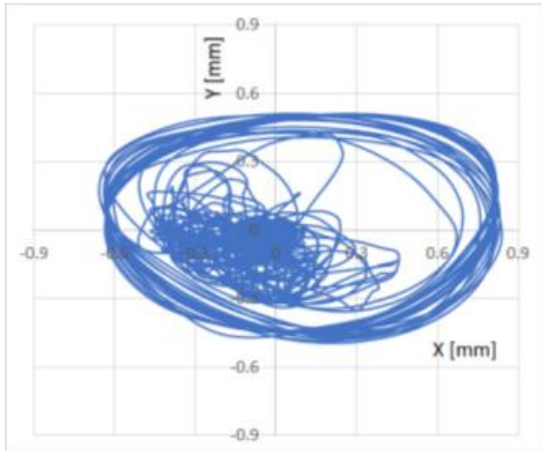

Figure 22 *Orbital x-y trajectory after power shut down.*

in Fig. 20. The supply power is switched by hand (switch 1) and the motor speed is decreased which produces the regenerated power. This regenerated power is supplied to AMB, using the switch 2. The regenerated currents of U, V and W phases are shown in Fig. 21. These currents are used to support the shaft by driving the HB type AMB. Before power shut down, the motor rotates stably by the PWM power amplifiers in the right upper of Fig. 20. The regenerated currents are zero until 200 ms in Fig. 21. After the supply power is shut down the regenerated currents are suddenly increased up to 200 mA and the rotating speed is decreased. But the regeneration time is short (about 300 ms) as shown in Fig. 21. This is considered that the shaft is thin and does not have enough inertial power. The orbital trajectory is shown in Fig. 22. Before power shut down the orbital trajectory remains within the magnitude of 0.05 mm around the center. After power shut down the trajectory increases quickly and the shaft touches down to the emergency bearing safely.

4. Concluding remarks

Two pole IPM type motor is developed to test the active magnetic bearing support for unexpected power shut down. The motor can run up to 12,000 rpm. Small hybrid magnetic bearing is used to support the one end of the rotor and another end is supported by a ball bearing. The stable rotating levitation is recognized up to 12,000 rpm. At the rotating speed of 8,000 rpm this system is tested when the power is unexpectedly shut down. The test results show possibility of supporting the rotor shaft for short time and the shaft speed is reduced by the regenerative brake quickly. This regenerated power can drive the magnetic bearing until the shaft speed decreases and touch down to emergency bearing.

However the regenerated power is not enough due to the low rotary inertia of the shaft. Also the regenerative circuit should be improved to decrease the shaft speed quickly and to produce the regenerated power more effectively.

Acknowledgment

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