SENSORLESS SPEED CONTROL OF A PERMANENT MAGNET TYPE AXIAL GAP SELF-BEARING MOTOR.

Dich Quang Nguyen
Dept. of Mechanical Eng., Ritsumeikan Uni., 1-1-1 Nojihigashi, Kusatsu, Shiga 525-8577, Japan.
E-mail: gr046070@se.ritsumei.ac.jp

Satoshi Ueno
Dept. of Mechanical Eng., Ritsumeikan Uni., 1-1-1 Nojihigashi, Kusatsu, Shiga 525-8577, Japan.
E-mail: sueno@se.ritsumei.ac.jp

Abstract—This paper presents an analytical and experiment evaluation of sensorless speed vector control of a permanent magnet type axial gap self bearing motor, in which rotor speed and position are estimated by using state observer, not by using mechanical encoder or resolver... The approach is based on the estimation of the motor back-EMF (or induced voltage) through a state observer with help of measured stator currents and reference voltages. In order to achieve an accurate estimation of the rotor speed and position, adaptive gain of observer controller is proposed. The experiment is implemented based on dSpace1104 with two three phase inverters. Results confirm that axial force and rotating torque can be controlled independently and motor can get the good performance in steady state at the average and high speed range.

I. INTRODUCTION

Recently, magnetic bearing-motor becomes more interesting in many researches thanks to its advantages such as high speed range, less maintenance and working ability in harsh environment... due to its noncontact levitating capability. Normally, magnetic bearing-motor has structures like a rotary motor installed between two radial magnetic bearings or combination of rotary motor and radial magnetic bearing with an axial bearing at one end. However, it makes machines increase in size and weight, which causes problems in some applications that have limit space, on the other hand, its control system is also complicated [1],[2]. For many applications, simpler and smaller construction and less complex control system are desirable. Satoshi Ueno has introduced an axial gap self-bearing motor (AGBM) which is a combination of a disc motor and axial magnetic bearing, it is quite simpler in structure and control than conventional magnetic bearing-motor since hardware component can be reduced [3],[4],[5],[6].

Figure 1 shows the schematic of an axial gap self-bearing motor. The radial motions x, y, θ_x, θ_y of the rotor are constrained by radial magnetic bearings such as the repulsion bearing shown. Only rotational motion θ and translation z of rotor along z axis are considered. The motor has two degrees of freedom. The rotor is a flat disc with permanent magnet (PM) attached on two faces of disc to achieve a nonsalient-pole rotor. Two stators, one in each size of rotor, have three-phase windings so as to generate the rotating magnetic flux in the air gap that produces the motoring torque T to the rotor and generates the attractive force between the rotor and the stators F_1 and F_2. The axial force F is the difference between two attractive forces and is controlled by changing the magnitude and phase of the currents in stator 1 and 2 with respect to rotor. Since the attractive magnetic force is unstable, axial position feedback control is required to stabilize the axial direction.

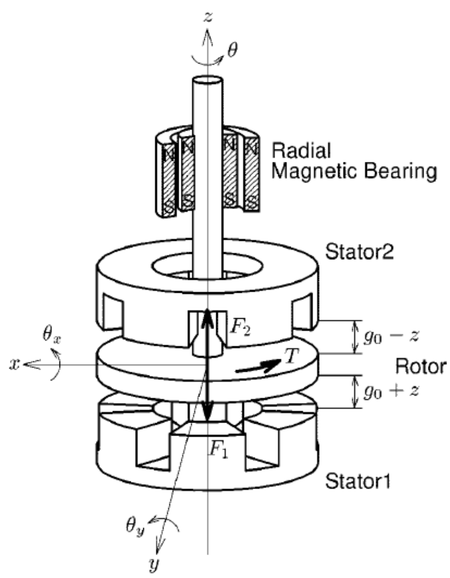

FIGURE 1: Structure of PM type AGBM.

In order to control its rotating torque independently from the axial force, the vector control is reasonable choice [5],[6]. But, for vector control of AGBM, it is necessary to obtain the rotor position for transforming co-ordinate. Normally, the rotor position can be obtained by a shaft mounted encoder or a resolver. These components will cause several disadvantages, such as increasing the drive system cost and size, noise immunity and reducing reliability. Therefore, the considerable sensorless control strategies have been proposed to solve the problems.

The conventional solutions for nonsalient-pole rotor machines rely on the dependence of the rotor position from the induced voltage in the stator windings [7]. These approaches are quite simple and they use the motor voltage equations to calculate the induced voltage from measured currents and voltages. Unfortunately, due to the open loop calculation, the estimation is very sensitive to system noises and parameters inaccuracy. As the induced voltage amplitude is proportional to the speed, estimation errors are very important at low speed, when the signal is too small to be sensed with a sufficient degree of rejection to the disturbances. Moreover, at standstill the position information is not available at all, leading to an uncontrolled movement of the rotor at start-up. The inclusion of feedback capability in the estimation strategy surely represents an improvement. State observers as Luenberger [8] and Sliding Mode [9], extended Kalman filters [10] and nonlinear observer [11] are proposed, in which the complete motor model is considered to estimate both the speed and the rotor position. Among the different approaches, the Luenberger Observer represents an attractive proposal because it has standard structure for linear systems and can be enhanced to apply for nonlinear systems, moreover it also has less computational charge and has specific design and tuning criteria. In addition, it is usually used for the initial condition error plants.

This paper presents a sensorless speed vector control system of the AGBM, in which the Luenberger observer is used to estimate the induced voltage by using measured stator phase currents and reference voltages and give rotor rotational position and speed. In order to confirm the proposed technique, experiments have been carried out and tested.

II. SENSORLESS CLOSED LOOP VECTOR CONTROL

A. Vector control scheme of AGBM

In this section, the control structure is derived and control methods of the axial force and motoring torque of AGBM are analyzed theoretically. Electrical model of AGBM is based on equations of the general theory of conventional AC electrical machines transformed to the stationary frame (α,β) or field oriented frame (d,q). But, it is very important to choose suitable transformation constants to keep the invariance principle of powers. It has been chosen as $\sqrt{2/3}$ instead of 2/3 as in conventional three phase motor. Further more, the self inductance of stator depends on air gap g between stator and rotor, so the stator phase inductance may be approximated by:

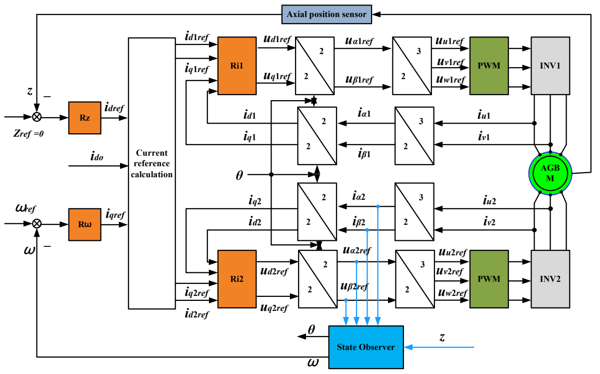

FIGURE 2. Sensorless control scheme of AGBM.

$$L_s = \frac{3}{2}\frac{L'_{s0}}{g} + L_{sl} \tag{1}$$

and mutual induction $L_m = \frac{3}{2}\frac{L'_{s0}}{g}$ (2)

with:

L'_{s0} : effective inductance per unit gap
L_{sl} : leakage inductance
g: air gap length between stator and rotor

The voltage vector equation for one side stator in stationary frame is as followed:

$$\boldsymbol{U}_s = \boldsymbol{i}_s\boldsymbol{R}_s + \boldsymbol{L}_s\frac{d\boldsymbol{i}_s}{dt} + \boldsymbol{e}_s \tag{3}$$

Here, $\boldsymbol{i}_s$ is stator current vector, $\boldsymbol{U}_s$ is stator voltage vector and $\boldsymbol{e}_s$ is induced voltage vector.

The motoring torque of AGBM can be controlled by q-axis current (i_q), while axial force can be controlled by d-axis current (i_d) [6], thus the control scheme proposed for the sensorless AGMB drive is shown in Figure 2. It is based on the vector control principle arranged in the d,q rotating frame, where d-axis is aligned with the rotor flux vector.

The axial displacement from the equilibrium point along the z-axis, z, can be detected by the gap sensor. The detected axial position is compared with axial position command z_{ref}, the error is inserted in the axial position controller R_z, the output of axial position controller is d-axis reference current. Position command z_{ref} is always set to zero to make sure the rotor is right in the midpoint between the two stators. The d-axis reference currents for the two stator windings i_{d1ref} and i_{d2ref} can be generated by using the offset current i_{d0} subtracting and adding i_{dref} respectively. The value of the offset current can be zero or a small value around zero.

Rotor speed calculated by state observer is compared with reference speed, then the difference is input of speed controller R_ω, the output of speed controller is the q-axis reference current, the q-axis reference currents for the two stator windings are same with this current.

The motor currents in the two-phase stator reference frame α,β are calculated by the measurement of two of the actual phase currents. Hence, the d,q components are obtained using the estimated rotor position from observer. The quadrature components are controlled to the reference value given by the speed controller, while the direct components are controlled to the reference value given by the axial position controller. The outputs of the current controllers, representing the voltage references, are then impressed to the motor using the Pulse Width Modulation technique (PWM), once an inverse transformation from the rotating to the three phase stator reference frame has been performed. All controllers are standard PI regulators except axial position controller (PID).

The rotor position observer is arranged in the two phase fixed α,β reference frame. The rotor position is calculated by means of the estimation of the induced voltage components in a state observer, using the instantaneous values of the motor phase currents and reference voltages.

B. Mathematical model of PM type AGBM

Since almost all observer designs are based on mathematical model of the plant, mathematical model of the motor is derived first. To perform the sensorless control of PM type motor, the model is generally generated in stationary frame (or αβ frame) due to the fact that rotor speed and position information are ready to be extracted in this reference frame.

From (3), the mathematical model of the AGBM in the two phases stator reference frame (α,β) can be expressed in the following equations:

$$\begin{cases} \dfrac{di_\alpha}{dt} = -\dfrac{R_s}{L_s} i_\alpha + \dfrac{1}{L_s} U_\alpha - \dfrac{1}{L_s} e_\alpha \\ \dfrac{di_\beta}{dt} = -\dfrac{R_s}{L_s} i_\beta + \dfrac{1}{L_s} U_\beta - \dfrac{1}{L_s} e_\beta \end{cases} \tag{4}$$

where U_α, U_β, i_α, i_β and e_α, e_β are the α-β components of respectively the stator voltage, current and induced voltage. For an ideal sinusoidal PM type AGBM, the induced voltage components in stationary frame can be described as:

$$\begin{cases} e_\alpha = -\lambda_m \omega_e \sin\theta \\ e_\beta = \lambda_m \omega_e \cos\theta \end{cases} \tag{5}$$

where λ_m is the amplitude of the flux induced by the permanent magnets of the rotor in the stator phases, ω_e is the electrical rotor angular speed and θ is the rotor position or magnet flux vector position.

It is obvious that, mechanical speed changes more slowly than other electrical variants, so it can be assumed that in short period the speed is constant so we can get:

$$\begin{cases} \dfrac{de_\alpha}{dt} = -\omega_e e_\beta \\ \dfrac{de_\beta}{dt} = \omega_e e_\alpha \end{cases} \tag{6}$$

From (5), rotor position and speed can be calculated as:

$$\theta = \arctan(-e_\alpha / e_\beta) \tag{7}$$

$$\omega_e = \frac{\sqrt{e_\alpha^2 + e_\beta^2}}{\lambda_m} \tag{8a}$$

or $$\omega_e = \frac{d\theta}{dt} \tag{8b}$$

The estimated velocity is calculated at a rate much lower than the rotor position estimation. The advantage of the formula (8a) is its ability to obtain reasonable accurate speed estimation. Its disadvantage is obvious that the result of velocity computation will depart as the effects of permanent magnet flux linkage λ_m, which may be changed as the temperature varies. The strength of formula (8b) is the accuracy of speed estimation throughout the medium to high speed range when rotor angle estimation is stable. The drawback to this method is the noise which results from the differentiation process. Especially, it will degrade the system response in the transient state.

C. Luenberger Observer

Since the original work by Luenberger, nowadays the state observers prove very useful tool to receive the information of the internal variables of a system that otherwise unknown. Luenberger observer is proposed in Figure 3, in which the complete motor model is considered to estimate both the speed and the rotor position. The difference between measured and estimated current is used for getting error, which multiplies with observer controller gain, the output of controller is correction factor Δ, which is added to the mathematical model and the process repeats every control cycle until error between two kinds of current is zero.

From equations (4) and (6), the state equation for Luenberger observer can be obtained when the induced

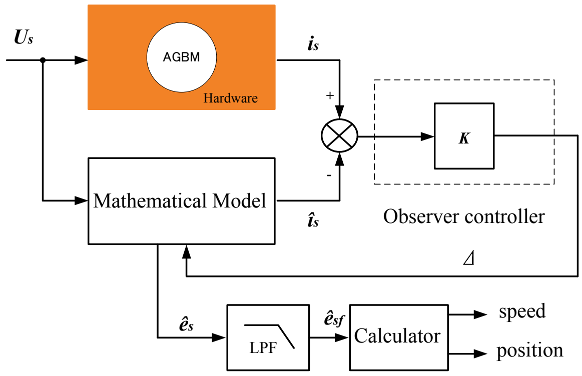

FIGURE 3: Structure of Luenberger observer.

voltage components can be considered as disturbances and included in the state vector, obtaining the following:

$$\begin{cases} \frac{d\hat{i}_\alpha}{dt} = \frac{1}{L_S} U_\alpha - \frac{1}{L_S} \hat{e}_\alpha - \frac{R_S}{L_S} \hat{i}_\alpha + \Delta_{i\alpha} \\ \frac{d\hat{i}_\beta}{dt} = \frac{1}{L_S} U_\beta - \frac{1}{L_S} \hat{e}_\beta - \frac{R_S}{L_S} \hat{i}_\beta + \Delta_{i\beta} \\ \frac{d\hat{e}_\alpha}{dt} = \Delta_{e\alpha} \\ \frac{d\hat{e}_\beta}{dt} = \Delta_{e\beta} \end{cases} \quad (9)$$

where $\begin{cases} \Delta_{i\alpha} = K_1 (i_\alpha - \hat{i}_\alpha) \\ \Delta_{i\beta} = K_1 (i_\beta - \hat{i}_\beta) \\ \Delta_{e\alpha} = K_2 (i_\alpha - \hat{i}_\alpha) \\ \Delta_{e\beta} = K_2 (i_\beta - \hat{i}_\beta) \end{cases}$ are correction factors.

and the symbol ^ indicates estimated variables, with reference to the extended state format we have:

$$\begin{cases} \dot{\hat{\boldsymbol{x}}} = \boldsymbol{A}\hat{\boldsymbol{x}} + \boldsymbol{B}\boldsymbol{u} + \boldsymbol{K}(\boldsymbol{i}_s - \hat{\boldsymbol{i}}_s) \\ \hat{\boldsymbol{y}} = \boldsymbol{C}\hat{\boldsymbol{x}} \end{cases} \quad (10)$$

where the matrices ***A*, *B*** and ***C*** are parameters of the state space model and ***K*** is a gain matrix, for the PM type AGBM, the gain matrix can assume as the following:

$$\boldsymbol{K} = \begin{bmatrix} \boldsymbol{K_i} & 0 \\ 0 & \boldsymbol{K_e} \end{bmatrix} \quad (11)$$

according to the symmetry of the equations respect to the α,β components, it will be received:

$$\boldsymbol{K_i} = \begin{bmatrix} K_1 & 0 \\ 0 & K_1 \end{bmatrix} \text{ and } \boldsymbol{K_e} = \begin{bmatrix} K_2 & 0 \\ 0 & K_2 \end{bmatrix} \quad (12)$$

The choice of gain factors must satisfy the necessary conditions for convergence of the system. The observer is called asymptotically stable if the observer error converges to zero at steady sate. The error between the actual and estimated state variables is:

$$\boldsymbol{\delta} = \boldsymbol{x} - \hat{\boldsymbol{x}} \quad (13)$$

Then, the error dynamic equation is:

$$\dot{\boldsymbol{\delta}} = (\boldsymbol{A} - \boldsymbol{KC})\boldsymbol{\delta} \quad (14)$$

Therefore, if the matrix ***(A – KC)*** has all the eigenvalues in the left half plane, as $t \to \infty$ the state error $\boldsymbol{\delta} \to 0$ i.e. the Luenberger observer is asymptotically stable. By using pole placement method with notice that the poles of the observer are usually chosen to converge 10 times faster than the poles of the system, we can get the gain matrix ***K***.

Further, the choice of the gain factor should also result from the compromise of assuring the operation of system all over the operating range (large gains) with the minimum ripple (small gains). In fact, large switching gain causes a great amount of ripple on the observed variables, which become very difficult for control. The solution proposed in this paper consists of adaptive gains proportional to the motor frequency, i.e. speed:

$$K_1 = K_{10}\omega_e \quad \text{and} \quad K_2 = K_{20}\omega_e \quad (15)$$

Unfortunately, the unavoidable ripple, which is caused by axial position controller and observer controller, affecting the estimated signals prevents the implementation of the vector control. Low pass filters (LPF) should be used in order to take out the noise and get the actual signal. Filter design must be accurately considered, the value of the cutoff frequency depends on the selection of the observer controller gain and is set experimentally. In this paper a digital filter is used for both the back-EMF components. It is obtained by the discretization of a continuous one-pole filter using a ZOH (Zero Order Hold). In fact, due to the low-pass characteristic, the filtered signals are reduced in amplitude and phase delayed respect to the inputs. In order to avoid the angular error which would arise because of using the filtered back-EMF signals, a proper compensation mechanism must also be implemented. The compensation value depends on motor speed, so in this experiment 30 speed ranges is separated, each speed range has its own slope and constant phase compensation component.

III. IMPLEMENTATION AND RESULTS

A. Control hardware

In order to confirm the proposed control method for PM type AGBM, an experimental setup has been made and experimentalized, which is shown distinctly in Figure 4. The rotor disc has a diameter of 55 mm and

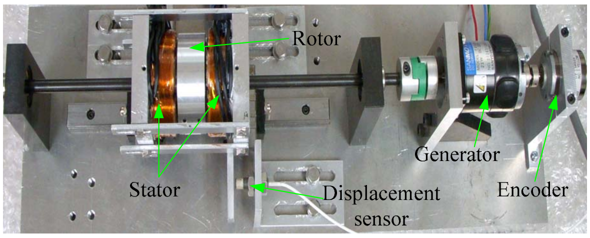

FIGURE 4: Image of the experiment setup.

four neodymium iron magnets with the thickness of 1.0 mm for each side attached to its surface to create two pole pairs. For experimental simplicity, the rotor is supported by two radial ball bearings in order to restrict the radial motion.

The stator has a diameter of 55 mm and six concentrated wound poles each with 200 coil turns. The stators can slide on linear guide to ensure the same desired air gap between rotor and two stators. A DC generator (Sanyo T402) is installed to give the load torque which is adjusted by changing the resistance, which is connected to outputs of generator. In order to measure the rotor position and speed in comparison with estimated values and the axial position for axial position feedback control, a rotary encoder (Copal RE30D) and an eddy-current-type displacement sensor (Sinkawa Co. Ltd. VC-202N) are installed, respectively.

The control hardware of sensorless AGBM drive is shown in Figure 5. It is based on a dSpace1104 board dedicated to control of electrical drives, which includes PWM units, general purpose input/output units (8 ADC and 8 DAC), encoder interface and so forth. The DSP reads the displacement signal from the displacement sensor via an A/D converter, and the rotor angle position and speed from the encoder via an encoder interface. Two motor phase currents are sensed, rescaled, and converted to digital values via an A/D converter. Then, the dSpace1104 calculates reference currents using the rotation control and axial position control algorithms and gives its commands to three phase inverter board. The AGBM is supplied by two three phase PWM inverters with a switching frequency of 20 kHz.

B. Experiment results

First, parameter estimation is carried out. The phase resistor is 2.6Ω. The static phase inductances are measured by measuring frequency response of the voltage versus current of the stator coil. We have $L'_{a0} = 11\times10^{-6}$ Hm and $L_{al} = 5\times10^{-3}$ H . Then, the inductances of (1) are received by calculating, we get $L_s = 17\times10^{-3}$ H . The air gap between the stator and the rotor is adjusted to 1.4 mm, including the magnet. Amplitude of the flux induced by the permanent magnets of the rotor in the stator phases can be estimated by measuring no load voltage of AGBM in

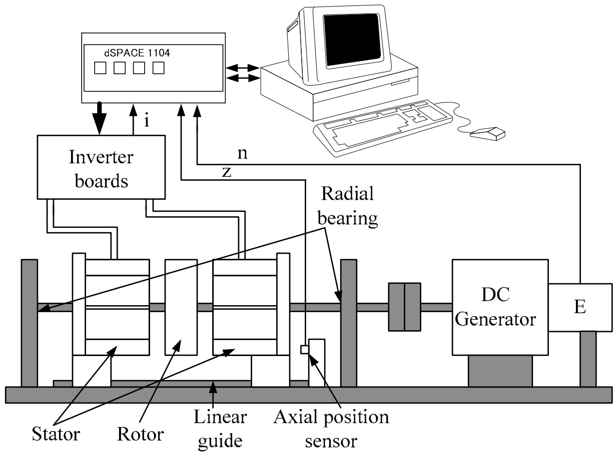

FIGURE 5: Overview of control hardware of AGBM.

generator mode, we have $\lambda_m = 0.022$ Wb . Rotor mass is 0.28 kg and rotor inertia is 0.000106 kgm^2.

Figure 6 presents the estimated back-EMF components by observer after using low pass filter with cutoff frequency 101 Hz at 500 rpm. Its sinusoidal shape shows that good estimation. Figure 7 shows the axial displacement of rotor at zero speed, first, the displacement error is set to 0.25mm, at time of 0.25s axial position controller starts to work. In transient state, the maximum error is 0.15mm, that is far smaller than air gap length at the equilibrium point and settling time is about 0.01s, then the displacement is almost zero in steady state. As low speed test presented in figure 8, the unloaded motor is running at 400 rpm when there is a sudden change in reference speed to 500 rpm. Figure 9 indicates the speed error between measured and estimated speed at steady state, the maximum error is about 5 rpm. The estimated speed shows some ripple, which is the consequence of the axial position controller and observer controller. This ripple may be improved by choosing suitable observer gain and parameters of axial controller. Figure 10 and figure 11 present the estimated and measured rotor position and the error between them at the steady state with rotating speed is 500 rpm, the maximum error is about 0.2 rad.

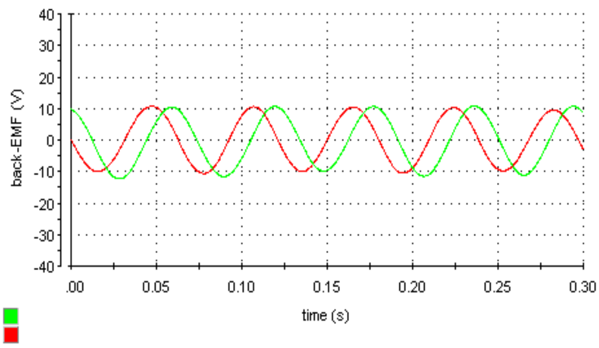

FIGURE 6: Estimated back-EMF components.

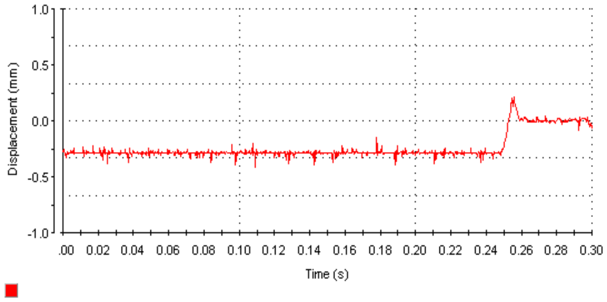

FIGURE 7: Axial displacement.

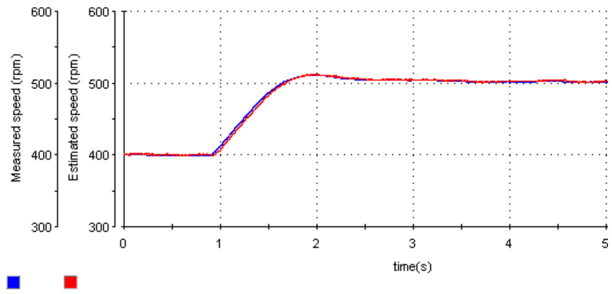

FIGURE 8: Measured and estimated speed

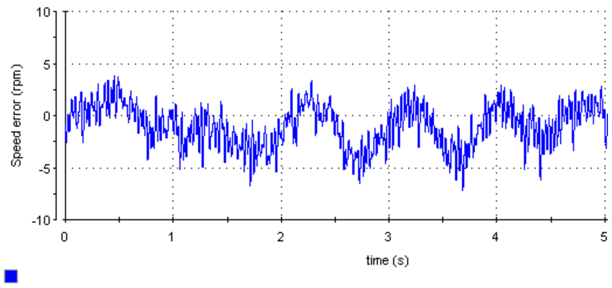

FIGURE 9: Steady state speed error at 500 rpm.

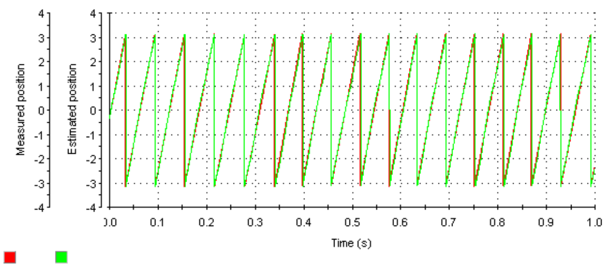

FIGURE 10: Measured and estimated rotor position

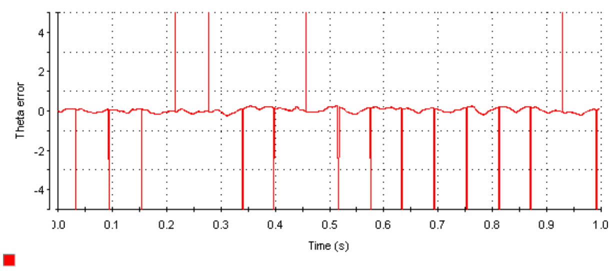

FIGURE 11: Position error (rad) at 500 rpm.

IV. CONCLUSION

Sensorless speed control method for the PM type AGBM is proposed and developed. Results from experiment confirm the good performance of the closed loop speed and axial position control. The axial position and rotating speed can be controlled independently. The performance of AGBM sensorless drives is good at medium and high speed range (over 10% norm speed) and in steady state. It is suitable for applications where low speed and standstill operations are not required. The major problem in experiment is represented by the ripple, which is caused by axial position controller, affecting the estimated variables. Further work is being continued to improve the experiment for this proposal.

REFERENCES

1. A. Chiba, T. Deido, T. Fukao and M. A. Rahman, “An analysis of bearingless AC motors”, IEEE Trans. Energy Conversion, vol. 9, pp. 61-67, Mar. 1994.

2. Y. Okada, K. Dejima and T. Ohishi, “Analysis and comparison of PM synchronous motor and induction motor type magnetic bearing”, IEEE Trans. Industry Applications, vol. 32, pp. 1047-1053, Sept./Oct. 1995.

3. Y. Okada, S. Ueno, T. Ohishi, T. Yamane and C. C. Tan, “Magnetically levitated motor for rotary blood pumps”, Artif. Organs, vol. 21, no. 7, pp. 739-745, 1997.

4. Y. Okada, T. Masuzawa, K. Matsuda, K. Ohmori, T. Yamane, Y. Konishi, S. Fukahori, S. Ueno and S. J. Kim, “Axial type self bearing motor for axial flow blood pump”, International Society for Artificial Organs vol. 27, pp. 887-891, 2003.

5. S. Ueno and Y. Okada, “Vector control of an induction type axial gap combined motor-bearing”, in Proc. of the IEEE Int. Conf. on Advanced Intelligent Mechatronics, Sept. 19-23, 1999, Atlanta, USA, pp. 794-799.

6. S. Ueno and Y. Okada, “Characteristics and control of a bidirectional axial gap combined motor-bearing”, IEEE Transactions on Mechatronics, Vol. 5, No. 3, Sept. 2000, pp. 310-318.

7. R. Wu, G.R. Slemon "A Permanent Magnet Motor Drive without a Shaft Sensor", IEEE Trans. Ind. Applications, vol. 27, no. 5, Sept./Oct. 1991, pp. 1005-1011.

8. L.A. Jones and J.H. Lang, “A state observer for the permanent magnet synchronous motor”, IEEE Trans. Ind. Electronics, Vol. 36, No. 3, pp. 374-382, August 1989.

9. F. Parasiliti, R. Petrella and M. Tursini, “Sensorless speed control of a PM synchronous motor by sliding mode observer”, Proc. ISIE ‘97, Vol. 3, pp. 1106-1111, Guimarães, 1997.

10. A. Germano, F. Parasiliti and M. Tursini, “Sensorless speed control of a PM synchronous motor by Kalman filter”, Proc. of ICEM , Vol. 2, pp. 540-544, Paris, September 1994.

11. Cristian De Angelo, Guillermo Bossio, Jorge Solsona, Guillermo O. García, and María Inés Valla, “A Rotor Position and Speed Observer for Permanent-Magnet Motors With Nonsinusoidal EMF Waveform”, IEEE Trans. Industrial Electronics, vol. 52, no. 3, pp. 807-813, June 2005.

12. A. Chiba, et. al., Magnetic Bearings and Bearingless Drives, 1st edition, Elsevier, Great Britain, 2005.