AN INDEPENDENT CONTROLLER OF RADIAL FORCE SUBSYSTEM FOR SUPER-HIGH-SPEED BEARINGLESS INDUCTION MOTORS

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ABSTRACT

The bearingless machines which combine the magnetic bearing and motor, is a great progress in recent years of research field of the high speed electrical machinery. Among them the bearingless induction motor (BLIM) is quite paid attention to because of its capability of easily weakening flux and high reliability. The BLIM is a strong coupled complicated nonlinear system. For the high accuracy requirement for the real-time control of air gap flux linkages, the various decoupling control algorithms can not realize this motor operating at super high speed at present. In this paper, an independent control strategy of radial force subsystem is proposed to realize the super high speed operation of BLIM. The air gap flux linkages of motor windings and radial force windings which are required can be identified accurately by the method of simpler voltage-model, in which the two only motor parameters-stator resistance and stator leakage are estimated by LSE based on zero-sequence voltage equations simultaneously. The current regulated PWM inverter is replaced by the air gap flux linkages regulated PWM inverter to improve control precision of air gap flux linkages. In order to reduce time delay of control system, the control period of radial force subsystem can be shortened to a great extent through right resource distribution in digital control systems.

INTRODUCTION

High speed and super-high-speed electric machines are being used for spindles, pumps, compressors, flywheels, Aero-Space, etc. The bearing technology has been the “bottleneck” of the development of high speed electrical machines. Magnetic bearings are widely used in the high speed electrical machines for the advantages of no contact, no lubrication, and no maintenance. However, considerable axial length and low axial utilization ratio for electric machines itself result in decreased critical speed and lower output power, and the microminiaturization is also limited. On the other hand, the cost is another unfavorable factor for the magnetic bearing applications.

The structure of magnetic bearing is similar to that of the ac. motor, and the combination of magnetic bearings and ac. motor which have the function of rotation and self-levitation with the aid of power electronics and microcomputer control is highly desirable. This novel electrical machines named “bearingless motor” came forth in [1]. Since the idea of configuration with $2p_1$ -pole motor windings and $2(p_1 \pm 1)$ -pole radial force windings in one stator, and the decoupling controller of the electromagnet torque and radial force based on vector controller of induction motors and permanent magnet synchronous motors, are proposed, the bearingless motors begin to be paid close attention to. So far, the bearingless technologies for induction motors, permanent magnet synchronous motors, synchronous reluctance motors, homo-polar motors, switched reluctance motors are proposed and further investigated in succession [2]-[10]. The bearingless motor has many advantages over traditional high speed motor with magnetic bearings. First of all, based on the magnetizing field of motor windings, the power for levitation control can be decreased. Moreover, it has shortened shaft length, enabled compactness and high speed or high power operations with high reliability. Bearingless motors have widened the applications of high speed drives, such as applications in biotechnology, chemical, medical, semiconductor, nuclear and miniature motor, etc.

There are various types of bearingless motors, among them the BLIM receives the extensive attention due to its simple structure and high reliability. The rotor levitation is the result of interaction of the motor windings and radial force windings in the stator. Coupling exists between the electromagnet torque and radial force inherently, so the BLIM is a nonlinear system more complicated than general induction motor. The decoupling control of the electromagnet torque and radial force is the key to the stable operation of bearingless motor. Moreover, as to classical static biased magnetic field of magnetic bearing, the rotation biased magnetic field of BLIM (or air gap motor flux) requires control system has high real-time control performance extremely for super high speed operation. It is a real problem in this field. Typical control algorithms at present treat the BLIM as a coupling nonlinear big system. Through coordinate transformation, this big system can be divided into two subsystems: electromagnet torque subsystem and radial force subsystem, firstly, two subsystems coupling by the item of air gap motor flux linkages [11]-[13]. The decoupling linearization control for subsystems can be realized by the air gap motor flux oriented vector controller [11]-[12]. Complexity in control structure and long control period make it difficult for control algorithms at present to meet the requirement of BLIM operating at super high speed.

In this paper, an independent control strategy of radial force subsystem is proposed to realize the super high speed operation of BLIM. The air gap flux linkages of motor windings and radial force windings which are required by independent controller can be identified accurately based on the simpler voltage-model, in which the two only motor parameters-stator resistance and stator leakage are estimated by LSE based on zero-sequence voltage equations simultaneously. The current regulated PWM inverter is replaced by the air gap flux linkages regulated PWM inverter to improve control precision of air gap flux linkages of radial force windings. In order to reduce time delay of control system, the control period of radial force subsystem is shortened to a great extent through right resource distribution in digital control systems based on double DSP. At last, experiment system is introduced.

THE RADIAL FORCE EQUATIONS

For an air gap flux density *B*, the Maxwell-Forces element which acts on a surface element dA of rotor is

$$dF = \frac{B^2 dA}{2\mu_0}, \tag{1}$$

where μ_0 is the vacuum or air permeability.

The total air gap flux density produced by motor windings and radial force windings is given by

$$\begin{aligned} B(\varphi,t) &= B_1(\varphi,t) + B_2(\varphi,t) \\ &= \hat{B}_1 \cos(p_1\varphi - \omega_1 t + \mu) + \hat{B}_2 \cos(p_2\varphi - \omega_1 t + \lambda) \end{aligned}, \tag{2}$$

where λ and μ are phase angles, φ is space rotation position angle, subscripts “1”, “2” correspond to motor windings and radial force windings, respectively, the same below.

By substituting (2) into (1) and integrating, when $p_2 = p_1 \pm 1$, the controllable Maxwell -Forces (or radial forces) in x- and y- direction can be expressed as

$$F_x = F_M \cos(\lambda - \mu), \tag{3}$$

$$F_y = \mp F_M \sin(\lambda - \mu)\,, \tag{4}$$

where the amplitude of Maxwell-Forces is

$$F_M = \frac{lr\pi\hat{B}_1\hat{B}_2}{2\mu_0}\,; \tag{5}$$

l is active length of the motor; r is rotor radius.

From (3-4), it can be concluded that the radial forces are closely related with the amplitude and relative position of two kinds of air gap flux.

Air gap flux (per pole) can be written as

$$\phi_1 = \frac{2lr\hat{B}_1}{p_1},\quad \phi_2 = \frac{2lr\hat{B}_2}{p_2}\,. \tag{6}$$

Air gap flux linkages (per phase) can be written as

$$\psi_1 = \phi_1 W_1,\quad \psi_2 = \phi_2 W_2\,, \tag{7}$$

where W_1 and W_2 are number of turns for the motor windings and radial force windings, respectively.

Neglecting the induced current in the rotor produced by the radial force windings, one can write

$$\psi_2 \approx L_{2m} i_{2s}\,, \tag{8}$$

where L_{m2} is mutual inductance of radial force windings.

Substitution of (6-8) into (5), yields,

$$F_M = \frac{\pi p_1 p_2 L_{2m} \psi_1 i_{2s}}{8lr\mu_0 W_1 W_2}\,. \tag{9}$$

Based on the vector multiplication operation ($\dot{\psi}_1 \times \dot{i}_{s2}$ and $\dot{\psi}_1 \bullet \dot{i}_{s2}$), (3-4) can be expressed in synchronous rotating reference frame as (power conservative transformation $d.q.0$)

$$F_x = k_M (i_{2sd}\psi_{1d} + i_{2sq}\psi_{1q})\,, \tag{10}$$

$$F_y = \pm k_M (i_{2sq}\psi_{1d} - i_{2sd}\psi_{1q})\,, \tag{11}$$

where $k_M = \dfrac{\pi p_1 p_2 L_{m2}}{12lr\mu_0 W_1 W_2}$, ψ_{1d} and ψ_{1q} are air gap motor flux linkages components; i_{2sd} and i_{2sq} are stator current components of radial force windings.

Neglecting additive torque effect, the electromagnet torque of BLIM is

$$T_e = p_1(\psi_{1d} i_{1sq} + \psi_{1q} i_{1sd})\,, \tag{12}$$

where i_{1sd} and i_{1sq} are stator current components of motor windings.

One can obtain from (10-12) that the radial force and electromagnet torque are both functions of air gap motor flux linkages by which coupling each other. In the air gap motor flux reference frame, $\psi_{1d} = \psi_1$; $\psi_{1q} = 0$; so (10-12) can be written as

$$F_x = k_M i_{2sd} \psi_1\,, \tag{13}$$

$$F_y = k_M i_{2sq} \psi_1\,, \tag{14}$$

$$T_e = p_1 \psi_1 i_{1sq}\,. \tag{15}$$

From (13-15), it can be known that once the air gap motor flux oriented control is realized ($\psi_1 = const.$), electromagnet torque and radial force of BLIM can be controlled by the current in motor windings and current in radial force windings, respectively. This is the typical decoupling algorithm at present.

LIMITATIONS OF THE CONTROL ALGORITHMS AT PRESENT

Due to the complexity of the decoupling algorithm

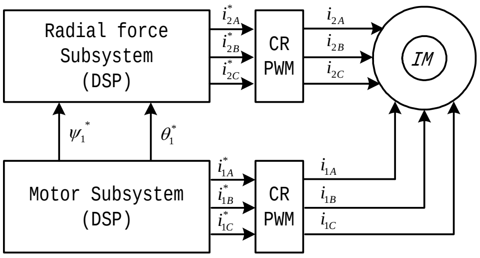

FIGURE 1: Control algorithm at present

based on the air gap motor flux oriented vector controller, the control period of single Digital Signal Processing (DSP) is relatively long. For the real-time control, each subsystem is controlled by one DSP generally. The amplitude and phase of air gap motor flux linkages are transmitted through dual DSP communication between two subsystems (electromagnet torque subsystem and radial force subsystem). The control algorithm is shown in FIGURE 1.

Some limitations of the algorithms mentioned above for high speed operation of BLIM are as follows:

- Stable suspension of BLIM requires high accuracy phase information of air gap motor flux linkages. It is indicated that phase error can not exceed 10 degrees in [4]. However, the communication delay time of dual DSP can be up to one control period of motor subsystem, which must be shortened to reduce the phase error. For example, the control period can not exceed 13.9 microseconds generally for the stable operation of BLIM at 60,000rpm. For special-purpose high performance DSP, such as TMS320LF2407A and ADMC401 for motor control can not satisfied with requirement of super high speed operation. Other high performance DSP not especially for motor control can meet this requirement, but it need to design complicated peripheral circuits, practicability is limited.
- There are some limitations in the air gap motor flux oriented controller, such as pull-out torque, sensitivity to the rotor parameters[14]-[15]. Moreover, highly nonlinearity makes it difficult for this controller to introduce effective algorithms of adaptive control or speed sensorless techonologies. Applications for the servo system with high accuracy and super high speed applications are limited. Finally, this controller can't be compatible with common used inverter (generally based on rotor flux oriented controller). Its practicability is limited also.

Due to facts mentioned above, the maximum speed of BLIM has not exeed 30,000rpm [16]-[17], control system design for super high speed BLIM is a difficult problem urgently to be solved.

In this paper, independent control strategy of radial force subsystem is proposed to realize the super high speed operation, the reasons are as follows:

- It is studied that air gap motor flux oriented controller is not necessary for decoupling control of BLIM[18]-[20]. If the amplitude and phase of air gap motor flux linkages are identified or measured by radial force subsytem itself, an independent control bewteen motor windings (or electromagnet torque subsystem) and radial force windings (or radial force subsystem) can be realized. In that case, air gap motor flux linkages deviations due to time delay in dual DSP communication can be eliminated.
- Although time delay exists inherently in any controller, in order to meet the requirement of real time control of radial force subsystem, the control period of radial force subsystem can be shortened to a great extent by optimizing resources of new DSP-TMS320F2812.
- Once an independent control strategy for radial force subsystem is realized, the control method for motor windings (or electromagnet torque) is no longer restricted by air gap motor flux oriented controller, and can adopt any kind of control techniques for induction motor in principle. It can adopt classical rotor motor flux oriented controller which is compatible with inverter in common use, or adopt speed sensorless technology for super high speed operation. This has undoubtedly increased commonability and practicability of BLIM.
- The air gap motor flux linkages can be measured by search coil around the stator teeth, or on-line identified by nonlinear method. In view of practicality, on-line identification method is more desirable.

IMPLEMENTATION OF INDEPENDENT CONTROL STRATEGY FOR RADIAL FORCE SUBSYSTEM FOR HIGH SPEED OPERATION

Implementation of independent control strategy for radial force subsystem must solve following key problems:

1 Acurate identification of air gap motor flux linkages

In this paper, air gap motor flux linkages are identified based on the following simpler voltage model:

$$\psi_{1s\alpha\beta} = \int \left(u_{1\alpha\beta} - R_{1s} i_{1s\alpha\beta} \right) dt \,, \tag{16}$$

$$\psi_{1\alpha\beta} = \psi_{1s\alpha\beta} - L_{1sl} i_{1s\alpha\beta} \,, \tag{17}$$

where

$\psi_{1s\alpha\beta}$ are stator motor flux linkages components in static reference frame $\alpha, \beta, 0$;

$\psi_{1\alpha\beta}$ are air gap motor flux linkages components in static reference frame $\alpha, \beta, 0$;

$u_{1s\alpha\beta}$ are stator voltages of motor windings in static reference frame $\alpha, \beta, 0$;

$i_{1s\alpha\beta}$ are stator currents of motor windings in static reference frame $\alpha, \beta, 0$;

R_{1s} is stator resistance of motor windings; L_{1sl} is stator leakage inductance of motor windings.

From (16-17), the identificaton algorithm is only related to two motor parameters: stator resistance and stator leakage inductance. In case of detuning (saturation, temperature effects, weakening flux for high speed opeation, etc.), the actual valves of two parameters change greater compared with initial values which are measured approximately on the basis of equivalent T circuits. The deviations of the parameters reduce the identification precision of air gap motor flux linkages, so the stable suspension of BLIM can not be maintained. In this situation, a method of online estimation of two only motor parameters- stator resistance and stator leakage inductance by LSE based on zero-sequence voltage equations proposed in [21] is adopted in this paper.

Zero-sequence voltage equations:

$$u_{1s0} = R_{1s} i_{1s0} + L_{1sl} \frac{di_{1s0}}{dt} \,, \tag{18}$$

$$u_{1s0} = \frac{1}{\sqrt{3}} \left(u_{1a} + u_{1b} + u_{1c} \right), \tag{19}$$

$$i_{1s0} = \frac{1}{\sqrt{3}} \left(i_{1a} + i_{1b} + i_{1c} \right), \tag{20}$$

where u_{1s0} and i_{1s0} are zero-sequence voltage and current, u_{1a} , u_{1b} , u_{1c} , i_{1a} , i_{1b} and i_{1c} are phase voltages and phase currents of motor windings, respectively.

Least squares estimation regression equations:

$$\hat{y}(t|\theta) = \Gamma(t)\theta \,, \tag{21}$$

where $\hat{y}(t|\theta) = [u_{1s0}]$ is prediction vector;

$\Gamma(t) = [i_{1s0} \quad di_{1s0}/dt]$ is regression matrix;

$\theta = [R_{1s} \quad L_{1sl}]^T$ is parameter vector.

Only voltages and currents of motor windings are needed in above estimater. The estimation precision is not influenced by any other motor parameters. FIGURE 2 shows the identification algorithm of air gap motor flux linkages with on line parameters estimation.

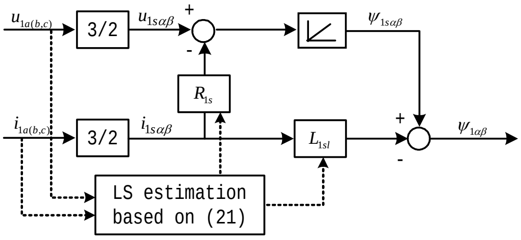

FIGURE 2: Identification air gap motor flux linkages with on line parameters estimation

2 Air gap flux linkages regulated PWM inverter

In present control algorithm of BLIM, the radial force windings are controlled by currents regulated PWM inverter on the assumption that radial force flux (air gap) can only be controlled by currents in radial force windings. However, for bearingless squirrel-cage rotor induction motor, additional currents are induced in rotor inevitably which deviating radial force flux. To deal with this problem, one can adopt phase compensation method proposed in [22]. But motor parameters deviation is a problem. Another method is scheming special pole-selective windings of a squirrel-cage rotor for BLIM to reduce rotor induced currents of radial force windings [23]. However, this method lacks the commonability. In this situation, air gap flux linkages of radial force windings regulated PWM inerter proposed in [24] is adopted to control flux linkages directly. This method is as follows:

(3-4) can be expressed in static reference frame $\alpha, \beta, 0$ as

$$F_x = k_M^{'} (\psi_{1\alpha}\psi_{2\alpha} + \psi_{1\beta}\psi_{2\beta}) , \qquad (22)$$

$$F_y = \pm k_M^{'} (\psi_{1\alpha}\psi_{2\beta} - \psi_{1\beta}\psi_{2\alpha}) , \qquad (23)$$

where $k_M^{'} = \dfrac{\pi p_1 p_2}{12 l r \mu_0 W_1 W_2}$.

Given the radial force, the needed air gap flux linkages of radial force windings can be computed from (22, 23) as follows:

$$\begin{bmatrix} \psi_{2\alpha} \\ \psi_{2\beta} \end{bmatrix} = \frac{1}{k_M^{'} (\psi_{1\alpha}^2 + \psi_{1\beta}^2)} \begin{bmatrix} \psi_{1\alpha} & -\psi_{1\beta} \\ \psi_{1\beta} & \psi_{1\alpha} \end{bmatrix} \begin{bmatrix} F_x \\ F_y \end{bmatrix} . \qquad (24)$$

The air gap flux linkages of radial force windings which are required in air gap flux linkages regulated PWM inverter are identified by the same method for that of motor windings.

A control block diagram of radial force subsystem in which the air gap flux linkages of double windings are all identified by voltage models with motor parameters on line estimation, and radial displacements are controlled by negative feedback controller, is shown in FIGURE 3.

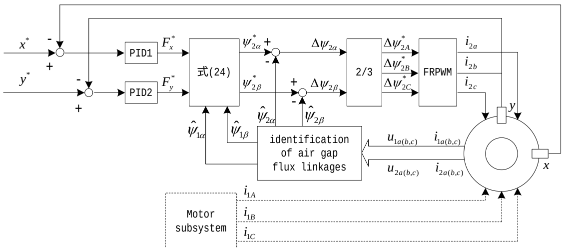

FIGURE 3: A control block diagram of radial force subsystem

3 Reduction of control period of radial force system

The computations of digital control system of radial force subsystem include identifications of air gap flux linkages of double windings, the regulations of air gap flux linkages of radial force windings, etc. If the control period of radial force subsystem is limited within 13.9 microseconds for the operation on 60,000rpm of BLIM, DSP of higher performance such as TMS320F2812 must be adopted, and computation resources must be rightly distributed also. Due to larger amount of computation, LS algorithm for estimation of stator resistances and stator leakage inductances of double windings based on regression equations can be completed by another DSP or combining with motor subsystem controller (vector control, speed sensorless, etc.).

Because stator resistance and stator leakage inductance are slower variational motor parameters compared with the one control period, the relay time effect can be neglected. So two parameters estimated can be transmitted through dual DSP communication between two subsystems. The improved control algorithm for radial force subsystem is shown in FIGURE 4.

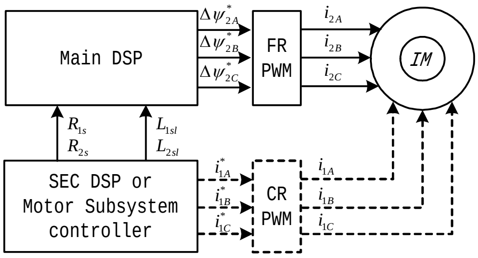

FIGURE 4: Improved control algorithm of BLIM

EXPERIMENT SYSTEM

The BLIM system with five-axis magnetic suspension comprises of one BLIM and an axial/radial integration magnetic bearing. A permanent magnet synchronous motor (PMSM) which exerts torque load and BLIM system make up whole experiment system without any couplings, as shown in FIGURE 5. Research work is going on. Some results will be issued in the articles afterwards.

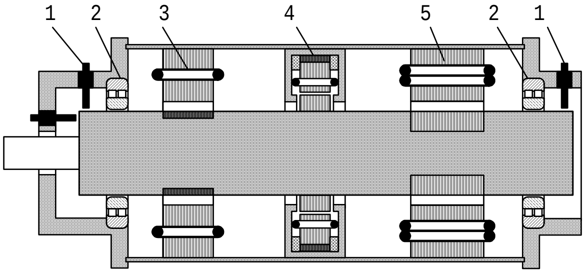

FIGURE 5: Experiment system

1.Gap sensor 2. Backup bearing 3. PMSM 4. BLIM

5. Axial/radial integration magnetic bearing

CONCLUSION

The independent control between motor windings and radial force windings is an effective way for the super high speed operation of BLIM. In this paper, key issues and methods for the independent control are proposed in details. The air gap flux linkages of radial force windings and bearing windings which are required can be identified accurately based on the simpler voltage-model under any operation conditions, in which the two only motor parameters-stator resistance and stator leakage inductance are estimated by LSE based on zero-sequence voltage equations simultaneously. Air gap flux linkages regulated PWM inverter is adopted to improve control precision of air gap flux linkages of radial force windings. In order to reduce time delay of control system and to improve controller stability, the control period of radial force subsystem is shortened to a great extent through right resource distribution in double DSP. The independent control for radial force subsystem makes motor windings have more flexibility in the choice of control methods, especially it can be controlled directly by general inverters. This improves the reliability, commonability and practicability of BLIM.

REFERENCES

1. R.Bosch, “Development of a bearingless electric motor,” in *ICEM*, 1988, pp.373-375.
2. J.Bichsel, “The bearingless electrical machine,” in *Proc.Int.Symp.Magnetic Suspension*, Technol. NASA Langley Res. Center, Hampton, 1991, pp.561-573.
3. A.Chiba, D.T.Power and M.A.Rahman, “Characteristics of a bearingless induction motor,” *IEEE Trans. Magnet.*, vol.27, no.6, pp.5199-5201, Nov. 1991.
4. R.Schöb, “Beiträge zur lagerlosen Asynchronmaschine,” *Dissertation ETH Zürich*, 1993.
5. A.Chiba, T.Deido, T.Fukao and M.A.Rahman, “An analysis of bearingless AC motors,” *IEEE Trans. Energy Conv.*, vol.9, pp.61-68, Mar. 1994.
6. A.Chiba, R.Furuichi, Y.Aikawa, K.Shimada, Y.Takamoto and T.Fukao, “Stable operation of induction- type bearingless motors under loaded conditions,” *IEEE Trans. Ind. Applicat.*, vol.33, pp. 919-924, July/Aug. 1997.
7. M.Oshima, S.Miyazawa, T.Deido, A.Chiba, F.Nakamura and T.Fukao, “Characteristics of a permanent magnet type bearingles motor,” *IEEE Trans. Ind. Applicat.*,vol.32, pp.363-370, Mar./Apr. 1996.
8. C.Michioka, T.Sakamoto, O.Ichikawa, A.Chiba and T.Fukao, “A decoupling control method of reluctance type bearingless motors considering magnetic saturation,” *IEEE Trans. Ind. Applicat.*, vol.32, pp.1204-1210, Sept./Oct. 1996.
9. O.Ichikawa, A.Chiba, T.Fukao, “Principles and structure of homopolar type bearingless motors,” in *Conf.Rec.IEEE-IAS Annu.Meeting*, 1999, pp.1223-1228.
10. M.Takemoto, H.Suzuki, A.Chiba, T.Fukao and M.A.Rahman, “Improved analysis of a bearingless switched reluctance motor,” *IEEE Trans. Ind. Applicat.*, vol.37, pp.26-34, Jan./Feb. 2001.
11. R.Schöb and J. Bichsel, “Vector control of the

bearingless motor," in *Proc.4th Int. Symp. Magnetic Bearings*, Zürich, Switzerland, 1994, pp.327-332.

12. T.Suzuki, A.Chiba, M.A.Rahman and T.Fukao, "An airgap flux oriented vector controller for stable magnetic suspension during high torque acceleration in bearingless induction motors," in *Conf.Rec.IEEE-IAS Annu.Meeting*, 1999, pp.1543-1550.
13. T.Satoh, S.Mori, M.Ohsawa, "Study of induction type bearingless canned motor pump," in *Proc. IPEC-Tokyo'2000*, 2000, pp.389-394.
14. R.W.De Doncker, D.W.Novotny, "The Universal Field Oriented (UFO) controller," *IEEE Trans. Ind. Applicat.*, vol.30, pp. 92-100, Jan./Feb. 1994.
15. R.W.De Doncker, F.Profumo, M.Pastorelli, P.Ferraris, "Comparison of universal field oriented (UFO) controllers in different reference frames," *IEEE Trans. Power. Electron.*, vol.10, pp.205 -213, Mar. 1995.
16. A.O.Salazar, A.Chiba, T.Fukao, "A Review of developments in bearingless motors," in *Proc.7th Int. Symp. Magnetic Bearings*, Zurich, Switzerland, 2000, pp.335-340.
17. W. Amrhein, S. Silber, K. Nenninger, G.Trauner, M. Reisinger, R. Schoeb, "Developments on bearingless drive technology," in *Proc.8th Int. Symp. Magnetic Bearings*, Mito, Japan, 2002, pp229-234.
18. K.Kiryu, T.Kuwajima, A.Chiba, T.Fukao, "A feedback controller with gap flux estimation in induction type bearingless motors," in *2000 National Convention I.E.E.*, Japan, 2000. pp.2090-2091.
19. K.Kiryu, T.Kuwajima, A.Chiba, T.Fukao, "A proposed controller for beaingless induction drives with search coils wound around stator teeth," in *Maglev2000.*, Rio de Janerio, Brazil, 2000. pp.435-440.
20. Deng Zhiquan, Wang Xiaolin, Zhang Hongquan, et al., "The nonlinear control of bearingless induction motors based on the motor rotor flux orientation," in *Proc CSEE.*, vol.23, pp.89-92, Mar. 2003.
21. C.B.Jacobina, J.E.C.Filho, A.M.N.Lima, "On-line estimation of the stator resistance of induction machines based on zero-sequence model," *IEEE Trans. Ind. Electron.*, vol.15, pp.346-353, Mar. 2000.
22. S.Nomura, A.Chiba, F.Nakamura, K.Ikeda, T.Fukao, M.A.Rahman, "A radial position control of induction type bearingless motor considering phase delay by the rotor squirrel cage," in *IEEE PCC-Yokohama'93*, 1993, pp.438-443.
23. A.Chiba, T.Fukao, "Optimal design of rotor circuits in induction type bearingless motors," *IEEE Trans. Magnet.*, vol.34, no.4, pp.2108-2110, Jul. 1998.
24. T.Satoh, M.Ohsawa, S.Mori, "Bearingless rotary machine," United States Patent No 6 078 119, Jun.20, 2000.