Decoupling Control for Bearingless Induction Motor with α-th Order Inverse System Theory *

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***Abstract* – A 5 degrees of freedom bearingless induction motor is a multi-variable, nonlinear and strong-coupled system. In order to achieve rotor suspension and operation steadily, it is necessary to realize dynamic decoupling control between torque force and suspension forces. In the paper, a method based on α-th order inverse system theory is used to study on dynamic decoupling control of bearingless induction motors. Firstly, the working principles of 3 degrees of freedom magnetic bearing and 2 degrees of freedom bearingless induction motor are analysed, the radial-axial force equations of 3 degrees of freedom magnetic bearing and the electromagnetic torque equation and radial force equations of the 2 degrees of freedom bearingless induction motor are given, and then the state equations of the 5 degrees of freedom bearingless induction motor are set up. Secondly, feasibility of decoupling control based on dynamic inverse theory for bearingless induction motor is discussed in detail, and the dynamic feedback linearization method is used to decouple and linearize the system. Finally, linear control system techniques are applied to these linearization subsystems to synthesize and simulate. The simulation results have shown that this kind of control strategy can realize dynamic decoupling control between torque force and suspension forces of the 5 degrees of freedom bearingless induction motor, and the control system has good dynamic and static performance.**

***Index Terms* –Bearingless induction motor, Magnetic bearing, Inverse system, Feedback linearization, Decoupling control**

I. INTRODUCTION

In this paper, an innovative 5 degrees of freedom bearingless induction motor, which is composed of a 3 degrees of freedom axial-radial magnetic bearing and a 2 degrees of freedom bearingless induction motor. 5 degrees of freedom bearingless induction motor is a non-linear and strong-coupling system, because there are couplings between the torque subsystem and flux linkage subsystem, in addition, there are couplings between radial force subsystems themselves. If the motor doesn't be taken some right decoupling control methods, the rotor of motor couldn't be suspended and the motor couldn't work steadily. In order to realize the innovative 5 degrees of freedom bearingless induction motor operation steadily and reliably, it is necessary to control the radial suspension forces, axial electromagnetic force of the magnetic bearings and torque, radial suspension forces of the 2 degrees of freedom bearingless induction motor independently. Therefore, α-th order inverse system method is used to study on decoupling control of the innovative bearingless induction motor in the paper [1].

II. DECOUPLING CONTROL OF BEARINGLESS INDUCTION MOTOR

A. The Radial and Axial Force Equations of 3 Degrees of Freedom Magnetic Bearing

Fig. 1 shows the structure diagram of 3 degrees of freedom radial and axial magnetic bearing [2]-[4]. In Fig. 1 (a), Φ_{la}, Φ_{lb} and Φ_{lc} are the magnet fluxes of the windings in *A*, *B* and *C* axis; Φ_{lx} and Φ_{ly} are the equivalent magnet fluxes projected from Φ_{la}, Φ_{lb} and Φ_{lc} to the axis of x_l and y_l; i_{la}, i_{lb} and i_{lc} are the currents of the windings in *A*, *B* and *C* axis; i_{la} and i_{lb} are the currents of equivalent windings in x_l and y_l axis. Then the Maxwell forces F_{lx} and F_{ly}, which generated by the composite fluxes of Φ_{la}, Φ_{lb} and Φ_{lc}, projected to the x_l and y_l axis in the Fig. 1(a) are as follows

$$\begin{bmatrix} F_{lx} \\ F_{ly} \end{bmatrix} = k_{ir} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{la} \\ i_{lb} \\ i_{lc} \end{bmatrix} = k_{ir} \begin{bmatrix} 1 & -\frac{1}{2} & --\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{lx} \\ i_{ly} \end{bmatrix}$$

$$= k_{ir} \begin{bmatrix} 3/2 & 0 \\ 0 & 3/2 \end{bmatrix} \begin{bmatrix} i_{lx} \\ i_{ly} \end{bmatrix} \tag{1}$$

where $k_{ir} = \dfrac{\mu_0 \cdot F_m \cdot N_r}{3({\delta_z}/{2S_z} + {\delta_r}/{3S_r})\delta_r}$, k_{ir} is the radial current coefficient; μ_0 is permeability of vacuum; δ_r is radial air gap; F_m is magnetic motive force of the permanent magnet; S_z is axial pole area; S_r is radial pole area; N_r is the turns of radial windings.

In the Fig. 1(b), Φ_z is the magnet flux of axial windings, Φ_p is the magnet flux of permanent magnet and i_z is the

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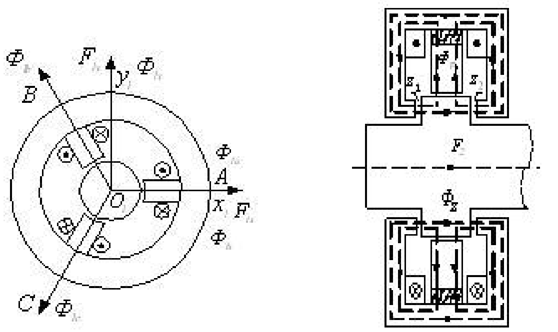

(a) 3-pole radial magnetic bearing (b) Magnetic circuit of axial magnetic bearing

current in z axis windings. Then, the equation of the axial force F_z of the rotor is as follows

$$F_z = k_{iz} i_z + k_z z \tag{2}$$

where k_{iz} is the axial current coefficient, $k_{iz} = \dfrac{\mu_0 \cdot F_m \cdot N_z}{(\delta_z/2S_z + \delta_r/3S_r)\delta_z}$; k_z is axial displacement coefficient, $k_z = -\dfrac{\mu_0 \cdot F_m^2}{2(\delta_z/2S_z + \delta_r/3S_r)^2 \delta_r S_z}$; δ_z is axial air gap; N_z is the turns of axial windings.

B. Working Principle of 2 Degrees of Freedom Bearingless Induction Motor and Principle of Radial Forces Generation

The stator of bearingless induction motor is wound 2-pole windings and 4-pole windings compoundly. The magnetic field produced by the 2-pole windings and the rotation magnetic field produced by the 4-pole windings affect each other in the gap. 2-pole windings are called as radial force windings. And the 4-pole windings are called as torque force windings, which produce rotation magnetic field and torque. The electrified torque windings will produce rotation magnetic field when bearingless induction motor work. If the electrified radial windings produce rotation magnetic field and the magnetic field of torque winding satisfy the following three conditions, then the interactional magnetic fields will produce radial suspension forces [5]-[6]: (1) P_4=P_2±1; (2) The two magnetic fields have the same rotation direction; (3) The currents which produce the magnetic field have the same frequency.

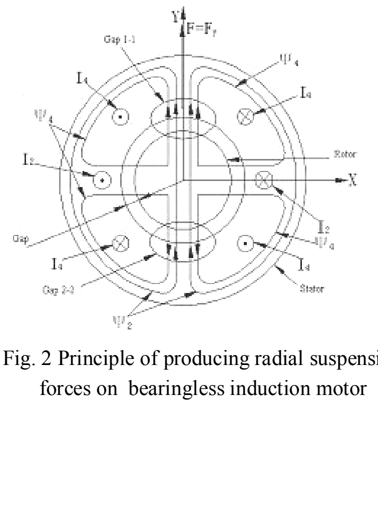

Fig. 2 Principle of producing radial suspension forces on bearingless induction motor

Fig. 2 shows the working principle of the bearingless induction motor. When 4-pole torque windings and 2-pole radial suspension windings have been electrified by I_4 and I_2 as the figure shown, it will generate the same direction of 4-pole torque flux linkage ψ_4 and 2-pole radial flux linkage ψ_2 in air gap 1-1, and the whole flux linkage will be increased to ψ_4+ψ_2, and electromagnetic suction force also be increased. While in air gap 2-2, ψ_4 and ψ_2 have the opposition direction, and the compound flux linkage will be decreased to ψ_4-ψ_2, and electromagnetic suction force will also be decreased, therefore, the rotor will be effected by electromagnetic compound force in the y positive direction. If the direction of current in suspension force windings will be changed, the radial electromagnetic compound force in y opposition direction will be generated. In the same way, electromagnetic compound force will be produced in x direction. So the rotor can be suspended in the balance central position by adjusting the magnitude and direction of the current in radial suspension force windings.

C. Analysis of Suspension Forces on Bearingless Induction Motor

2-pole radial suspension force windings and 4-pole torque windings are wound compoundly in slots of bearingless induction motor. The electromagnetic couplings of bearingless induction motor are very complex, because there are couplings between the 2-pole windings and 4-pole windings, and there are couplings between the windings themselves [3]. In order to analyse easily, 2-phase windings which has been changed from 3-phase windings in static coordinate through $C_{3/2}$ and $C_{r/s}$ transform is studied. Because the mutual inductance value between 4-pole windings and 2-pole windings is 0, the value of torque windings self-inductance L_{4s} and the value of radial windings self-inductance L_{2s} are constant. The inductance matrix of the motor $\boldsymbol{L}$ can be obtained as

$$\boldsymbol{L} = \begin{bmatrix} L_{4s} & 0 & -M'\alpha & M'\beta \\ 0 & L_{4s} & M'\beta & M'\alpha \\ -M'\alpha & M'\beta & L_{2s} & 0 \\ M'\beta & M'\alpha & 0 & L_{2s} \end{bmatrix} \tag{3}$$

where α and β are the rotor radial displacement in the direction of x and y. M' is the coefficient of mutual inductance of 4-pole windings and 2-pole windings. The subscript expression s is the component of self-inductance of the stator. According to the relationship of energy conversion, the magnetic energy stored in the windings can be written as

$$\boldsymbol{W}_m = \frac{1}{2}\boldsymbol{I}^{\mathrm{T}}\boldsymbol{L}\boldsymbol{I} \tag{4}$$

where $\boldsymbol{I} = \begin{bmatrix} i_{d4s} & i_{q4s} & i_{d2s} & i_{q2s} \end{bmatrix}^{\mathrm{T}}$ is current matrix. i_{d4s} and i_{q4s} are the 4-pole windings current component in d-q coordinate, respectively. i_{d2s} and i_{q2s} are the 2-pole windings current component in d-q coordinate, respectively.

Substituting the above variable into (4), (4) can be written as

$$W_m = \frac{1}{2}\begin{bmatrix} i_{d4s} & i_{q4s} & i_{d2s} & i_{q2s} \end{bmatrix}[\boldsymbol{L}]\begin{bmatrix} i_{d4s} \\ i_{q4s} \\ i_{d2s} \\ i_{q2s} \end{bmatrix} \tag{5}$$

Neglecting magnetic saturation, the F_{rx} and F_{ry} are the radial forces in the x- and y-directions, where $F_{rx}=\partial Wm/\partial\alpha$ and $F_{ry}=\partial Wm/\partial\beta$, can be written as

$$\begin{bmatrix} F_{rx} \\ F_{ry} \end{bmatrix} = \begin{bmatrix} \partial \boldsymbol{W}_m / \partial\alpha \\ \partial \boldsymbol{W}_m / \partial\beta \end{bmatrix} = M' \begin{bmatrix} -i_{d4s} & i_{q4s} \\ i_{q4s} & i_{d4s} \end{bmatrix}\begin{bmatrix} i_{d2s} \\ i_{q2s} \end{bmatrix} \tag{6}$$

D. Electromagnetic Torque of Bearingless Induction Motor

The electromagnetic forces, which make the rotor suspend and bearingless induction motor operate, are produced by interactional flux linkage of 4-pole windings and 2-pole windings. Because the magnetic field produced by radial force windings is very smaller than the magnetic field produced by torque force windings, neglecting the radial force windings magnetic field, the rotor flux linkage can be satisfied as the following equations

$$\begin{cases} \dot{\psi}_{dr} = -\dfrac{1}{T_r}\psi_{dr} - \omega_r \psi_{q4s} + \dfrac{L_{m4r}}{T_r} i_{d4s} \\ \dot{\psi}_{qr} = -\dfrac{1}{T_r}\psi_{qr} + \omega_r \psi_{d4s} + \dfrac{L_{m4r}}{T_r} i_{q4s} \end{cases} \tag{7}$$

The torque equation for bearingless induction motor is

$$T_e = p_4 \frac{L_{m4r}}{L_r}(\psi_{dr} i_{q4s} - \psi_{qr} i_{d4s}) \tag{8}$$

where ψ_{dr} and ψ_{qr} are the component of rotor flux linkage in d-q coordinate, respectively. ω_r is the speed of the rotor. ψ_{d4s} and ψ_{q4s} are the component of stator torque flux linkage in d-q coordinate, respectively. T_r is the time constant of rotor. p_4 is the pole-pair number of torque windings. L_{m4r} is the mutual inductance between torque windings and rotor.

E. Dynamic Equations of Rotor on Bearingless Induction Motor

Fig. 3 shows that the analysis of forces acting on the rotor of the 5 degrees of freedom bearingless inductiom motor. In the Fig. 3, the subscript "l" denotes 3 degrees of freedom magnetic bearing on the left side. The subscript "r" denotes the 2 degrees of freedom bearingless motor on the right side. "o" is the mass center of the rotor; x and y are the coordinate of the mass center of the rotor; o_l and o_r are the coordinate origins on the left and the right side, respectively. And redefine x_r and y_r as stationary coordinate, the system motion equation of the 5 degrees of freedom bearingless inductiom motor are as follows[7]

$$\begin{cases} m\ddot{x}_l + F_{lx} = f_{lx} \\ m\ddot{y}_l + F_{ly} = f_{ly} \\ m\ddot{z} + F_z = f_z \\ m\ddot{x}_r + F_{rx} = f_{rx} \\ m\ddot{y}_r + F_{ry} = f_{ry} \\ \dfrac{J}{p_4}\dot{\omega} = T_e - T_L \end{cases} \tag{9}$$

where m is the mass of the rotor; f_{lx}, f_{ly}, f_z, f_{ry} and f_{ry} are the external disturbance in the direction of x_l, y_l, z, x_r and y_r axis, respectively; J is the moment of inertia of the rotor; ω_r is the mechanical rotational angular speed of the rotor; T_e and T_L are the electromagnetic torque and the load torque, respectively.

State variables are chosen as

$$X=[x_1,x_2,\cdots,x_{12},x_{13}]^{\mathrm{T}} = \left[x_l,y_l,z,x_r,y_r,\dot{x}_l,\dot{y}_l,\dot{z},\dot{x}_r,\dot{y}_r,\omega_r,\psi_{dr},\psi_{qr}\right]^{\mathrm{T}} \tag{10}$$

Input variables are chosen as

$$U=[u_1,u_2,\cdots,u_6,u_7]^{\mathrm{T}} = \left[i_{lx},i_{ly},i_z,i_{d4s},i_{q4s},i_{d2s},i_{q2s}\right]^{\mathrm{T}} \tag{11}$$

Output variables are chosen as

$$Y=[y_1,y_2,y_3,y_4,y_5,y_6,y_7]^{\mathrm{T}} = [x_l,y_l,z,x_r,y_r,\omega_r,\psi_r]^{\mathrm{T}} \tag{12}$$

Substituting (1),(2), (6)~(8) and(10)~(12) into (9), the state equation of the system is written as

$$\begin{cases} \dot{x}_1 = x_6 \\ \dot{x}_2 = x_7 \\ \dot{x}_3 = x_8 \\ \dot{x}_4 = x_9 \\ \dot{x}_5 = x_{10} \\ \dot{x}_6 = \dfrac{1}{m}(-\dfrac{3}{2}k_{ir}u_1 + f_{lx}) \\ \dot{x}_7 = \dfrac{1}{m}(-\dfrac{3}{2}k_{ir}u_2 + f_{ly}) \\ \dot{x}_8 = \dfrac{1}{m}(-k_{iz}u_3 - K_z x_3 + f_z) \\ \dot{x}_9 = \dfrac{M}{m}(u_4u_6 - u_5u_7) + \dfrac{1}{m}f_{rx} \\ \dot{x}_{10} = -\dfrac{M}{m}(u_5u_6 + u_4u_7) + \dfrac{1}{m}f_{ry} \\ \dot{x}_{11} = \dfrac{P_4^{\,2}L_{m4r}}{JL_r}(x_{12}u_5 - x_{13}u_4) - \dfrac{P_4}{J}T_L \\ \dot{x}_{12} = -\dfrac{1}{T_r}x_{12} - x_{11}x_{13} + \dfrac{L_{m4r}}{T_r}u_4 \\ \dot{x}_{13} = -\dfrac{1}{T_r}x_{13} + x_{11}x_{12} + \dfrac{L_{m4r}}{T_r}u_5 \end{cases} \tag{13}$$

Output equation is written as

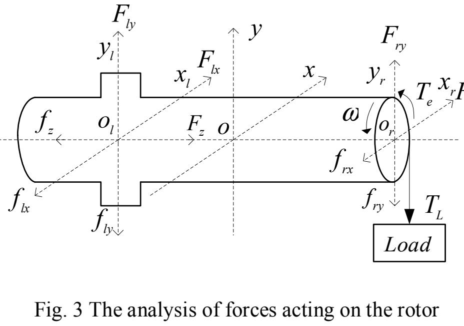

Fig. 3 The analysis of forces acting on the rotor

$$Y=\begin{bmatrix}y_1\\y_2\\y_3\\y_4\\y_5\\y_6\\y_7\end{bmatrix}=\begin{bmatrix}x_l\\y_l\\z\\x_r\\y_r\\\omega_r\\\psi_r\end{bmatrix}=\begin{bmatrix}x_1\\x_2\\x_3\\x_4\\x_5\\x_{11}\\\sqrt{x_{12}^{\ 2}+x_{13}^{\ 2}}\end{bmatrix} \tag{14}$$

It can be seen from (11) ~ (14) that the state equation of the 5 degrees of freedom bearingless induction motor is a 7-input and 7-output nonlinear system. Fig. 4 shows the state equation structure diagram of 5 degrees of freedom bearingless induction motor.

From (10) ~ (14), we can obtain as follows

$$\begin{cases}\dot{y}_1=\dot{x}_1=x_6\\ \ddot{y}_1=\dot{x}_6=\dfrac{1}{m}(-\dfrac{3}{2}k_{ir}u_1+f_{lx})\\ \dot{y}_2=\dot{x}_2=x_7\\ \ddot{y}_2=\dot{x}_7=\dfrac{1}{m}(-\dfrac{3}{2}k_{ir}u_2+f_{ly})\\ \dot{y}_3=\dot{x}_3=x_8\\ \ddot{y}_3=\dot{x}_8=\dfrac{1}{m}(-k_{iz}u_3-K_z z+f_z)\\ \dot{y}_4=\dot{x}_4=x_9\\ \ddot{y}_4=\dot{x}_9=\dfrac{M}{m}(u_4u_6-u_5u_7)+\dfrac{1}{m}f_{rx}\\ \dot{y}_5=\dot{x}_5=x_{10}\\ \ddot{y}_5=\dot{x}_{10}=-\dfrac{M}{m}(u_5u_6+u_4u_7)+\dfrac{1}{m}f_{ry}\\ \dot{y}_6=\dot{x}_{11}=\dfrac{P_4^2L_{m4r}}{JL_r}(x_{12}u_5-x_{13}u_4)-\dfrac{P_4}{J}T_L\\ \dot{y}_7=\dot{\psi}_r=-\dfrac{1}{T_r}\psi_r+\dfrac{L_{m4r}}{T_r}\dfrac{1}{\psi_r}\left(u_4x_{12}+u_5x_{13}\right)\end{cases} \tag{15}$$

Choose

$$A(u)=\begin{bmatrix}\ddot{y}_1\\\ddot{y}_2\\\ddot{y}_3\\\ddot{y}_4\\\ddot{y}_5\\\dot{y}_6\\\dot{y}_7\end{bmatrix}=\begin{bmatrix}\dot{x}_6=\dfrac{1}{m}(-\dfrac{3}{2}k_{ir}u_1+f_{lx})\\ \dot{x}_7=\dfrac{1}{m}(-\dfrac{3}{2}k_{ir}u_2+f_{ly})\\ \dot{x}_8=\dfrac{1}{m}(-k_{iz}u_3-K_z z+f_z)\\ \dot{x}_9=\dfrac{M}{m}(u_4u_6-u_5u_7)+\dfrac{1}{m}f_{rx}\\ \dot{x}_{10}=-\dfrac{M}{m}(u_5u_6+u_4u_7)+\dfrac{1}{m}f_{ry}\\ \dot{x}_{11}=\dfrac{P_4^2L_{m4r}}{JL_r}(x_{12}u_5-x_{13}u_4)-\dfrac{P_4}{J}T_L\\ \dot{\psi}_r=-\dfrac{1}{T_r}\psi_r+\dfrac{L_{m4r}}{T_r}\dfrac{1}{\psi_r}\left(u_4x_{12}+u_5x_{13}\right)\end{bmatrix} \tag{16}$$

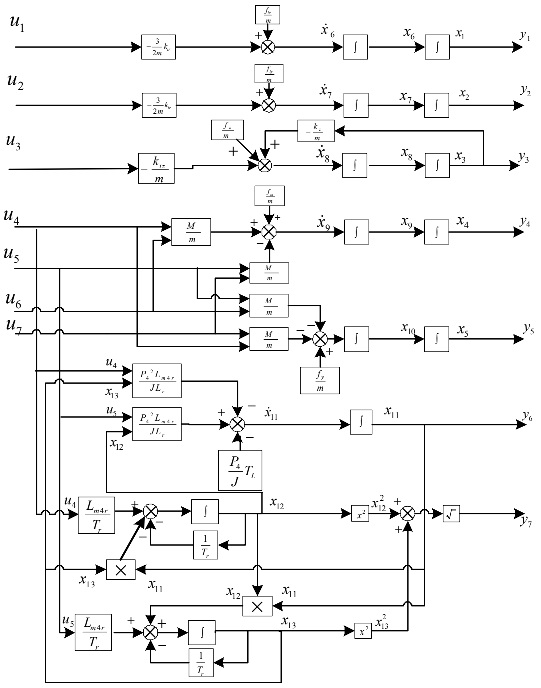

Fig.4 The state equation structure diagram of bearingless induction motor

Take the derivative of $\boldsymbol{A}(\boldsymbol{U})$ and obtain $rank\left[\dfrac{\partial A}{\partial U}\right]$ and the matrix $\dfrac{\partial \boldsymbol{A}}{\partial \boldsymbol{U}}$ is nonsingular. The relative orders of the system are as follows

$$\alpha=(\alpha_1,\alpha_2,\alpha_3,\alpha_4,\alpha_5,\alpha_6,\alpha_7)=(2,2,2,2,2,1,1)$$

It is easy to gain that $\sum_{i=1}^{r}\alpha_i=12$. And the order of state equation of the system is 13, so the system is invertible according to theorem [1]. The dynamic feedback linearization method are adopted, now suppose

$$\begin{cases}u_1=\phi_1\\ u_2=\phi_2\\ u_3=\phi_3\\ u_4u_6-u_5u_7=\phi_4\\ u_5u_6+u_4u_7=\phi_5\\ x_{12}u_5-x_{13}u_4=\phi_6\\ \dfrac{1}{\psi_r}\left(u_4x_{12}+u_5x_{13}\right)=\phi_7\end{cases} \tag{17}$$

From (17), the formulas of state feedback arithmetic is as follows

$$\begin{cases} u_1 = \phi_1 \\ u_2 = \phi_2 \\ u_3 = \phi_3 \\ u_4 = -\dfrac{x_{13}}{\psi_r^2}\phi_6 + \dfrac{x_{12}}{\psi_r}\phi_7 \\ u_5 = \dfrac{x_{12}}{\psi_r^2}\phi_6 + \dfrac{x_{13}}{\psi_r}\phi_7 \\ u_6 = \dfrac{u_4}{u_4^2+u_5^2}\phi_4 + \dfrac{u_5}{u_4^2+u_5^2}\phi_5 \\ u_7 = -\dfrac{u_5}{u_4^2+u_5^2}\phi_4 + \dfrac{u_4}{u_4^2+u_5^2}\phi_5 \end{cases} \tag{18}$$

Substituting (17) into (15), Substituting $f_{lx}=k_s x_l$, $f_{ly}=k_s y_l$, $f_z=k_s \cdot z$, $f_{rx}= k_s \cdot x_r$ and $f_{ry}=k_s \cdot y_r$ into (15), from (13)~ (15), we can obtain the formula as follows

$$\begin{cases} \ddot{x}_l = -\dfrac{3}{2m}k_{ir}\phi_1 + \dfrac{k_s}{m}x_l \\ \ddot{y}_l = -\dfrac{3}{2m}k_{ir}\phi_2 + \dfrac{k_s}{m}y_l \\ \ddot{z} = -\dfrac{1}{m}k_{iz}\phi_3 - \dfrac{1}{m}K_z x_3 + \dfrac{k_s}{m}z \\ \ddot{x}_r = \dfrac{M}{m}\phi_4 + \dfrac{k_s}{m}x_r \\ \ddot{y}_r = -\dfrac{M}{m}\phi_5 + \dfrac{k_s}{m}y_r \\ \dot{\omega}_r = \dfrac{P_4^2 L_{m4r}}{JL_r}\phi_6 - \dfrac{P_4}{J}T_L \\ \dot{\psi}_r = -\dfrac{1}{T_r}\psi_r + \dfrac{L_{m4r}}{T_r}\phi_7 \end{cases} \tag{19}$$

The state equation structure diagram of bearingless induction motor after decoupling control is shown in Fig. 5

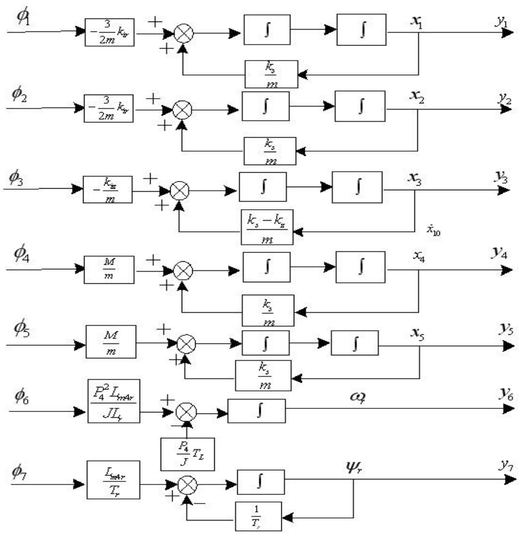

Fig.5 The state equation structure diagram of bearingless induction motor after decoupling control

III. SYNTHETIZING SYSTEM

A. Synthetizing Position of Rotor System

The normalized linear system described in (19) can be synthesized using the linear system theory. The former three rows of (19) are the magnetic bearing displacement subsystems; the fourth and fifth rows are the rotor displacement subsystems of bearingless induction motor which belongs to the second-order integral system. For example, the transfer function of the displacement system of the rotor in the direction of x_r axis is as follows

$$G_k(s)=x_r(s)/\phi_4(s)=\mathrm{M}/m \cdot s^2 \tag{20}$$

The characteristic equation of the system is as follows

$$s^2+2\xi\omega_n s+\omega_n^2=0 \tag{21}$$

The parameters ω_n and ξ are chosen ω_n =800 rad/s, $\xi=\sqrt{2}/2$, the transfer function of state feedback is as follows

$$a_0 s+a_1=2\xi\omega_n m/M \cdot s +\omega_n^2 m/M \tag{22}$$

The closed loop transfer function of the system can be obtained as follows

$$G(s) = \frac{6.4\times10^5}{s^2+1132s+6.4\times10^5} \tag{23}$$

The overshoot of the system is $\sigma = e^{-\frac{\xi}{\sqrt{1-\xi^2}}\pi} = 4.3\%$, the adjusting time is $t_s=4/\xi\omega_n$=7.06 ms.

B. Synthetizing Speed System

The sixth row of (19) is the subsystem of the speed ω_r, which belongs to the first-order integral system. The transfer function of the speed subsystem can be chosen

$$G_k(s) = \frac{\omega_r(s)}{\phi_6(s)} = \frac{P_4^2 L_{m4r}}{JL_r}\cdot\frac{1}{s} \tag{24}$$

The speed adjuster can be chosen as PI adjuster. The transfer function of the system is

$$G_c(s) = \frac{k_1(\tau s+1)}{\tau s} \tag{25}$$

According to requirement of the design adjuster theory, G_c(s) can be chosen as follows

$$G_c(s) = \frac{2JL_r(\tau s+1)}{P_4^2 L_{m4r}\tau^2 s} \tag{26}$$

The closed loop transfer function of the rotate speed system is as follows

$$\Phi(s) = \frac{2\tau^{-2}(\tau s+1)}{s^2+2\tau^{-1}s+2\tau^{-2}} \tag{27}$$

V. SYSTEM SIMULATION

The control strategy can be verified by simulating using the parameters of the designed prototype machine. The parameters of the system are as follows: The stator inductance L_s is 16.31×10^{-2} H; The rotor inductance L_r is 16.778×10^{-2} H; The mutual inductance between stator and rotor L_{m4r} is 15.856×10^{-2} H; The mutual inductance coefficient between stator torque winding and radial force winding M is 78.2 H/m; The rotor resistance r is 11.48 Ω; The time constant of the rotor T_r is 1.46×10^{-2} s; The quality of rotor m is 2.85 kg; The moment of inertia J is 0.00769 kg·m^2; The pole pairs of torque windings $P_4$is 2; The pole pairs of suspension windings P_2 is 3; We can obtain the feedback parameters of radial forces system are $a_0=2\xi\omega_n m/M=41.23$, $a_1=\omega_n^2 m/M=23324.81$ and the adjust parameter of torque system, from (25) and (26), $k_1=\dfrac{2JL_r}{P_z^2 L_{m4r}\tau}=0.041$,where τ is 0.1.

From (27) the closed loop transfer function is

$$\Phi(s)=\frac{2\tau^{-2}(\tau s+1)}{s^2+2\tau^{-1}s+2\tau^{-2}}=\frac{20s+200}{s^2+20s+200} \quad (28)$$

A. Process of Rotor Rising

When the initialization of x is –0.4 mm, the displacement curve starting up in x-direction is shown in Fig. 6. The simulation results have shown that the steady-state error of system approach to 0, the overshoot of system is very small and adjusting time is approach to 0.01 s. When the initialization of x is –0.4 mm and y is –0.2 mm, the trajectory of mass center of rotor is shown in Fig. 7. The rotor position subsystem of decoupling control for bearingless induction motor has fine dynamic and static performance.

B. System of Speed

The step response of the speed subsystem of bearingless induction motor is shown in Fig. 8. The expectation speed is 6 000 r/min, and the simulation results have shown that the overshoot of the system is less than 5% and the adjusting time is less than 0.6 s, so the speed subsystem has fine performance.

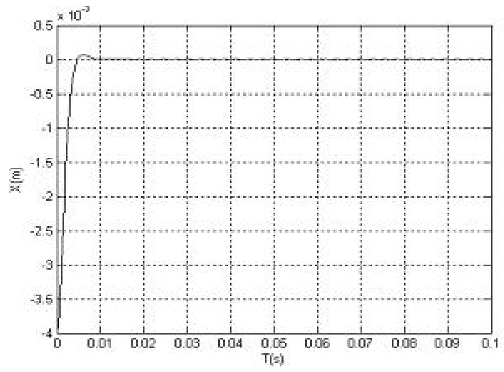

Fig. 6 Start up displacement curve in the x-direction

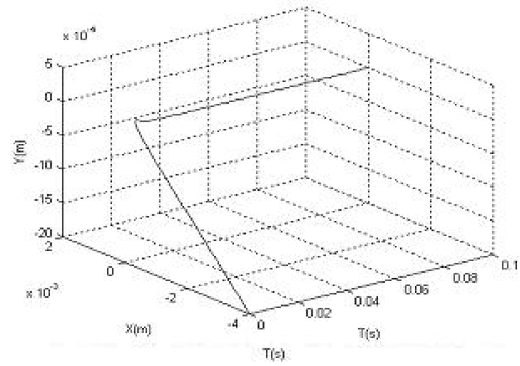

Fig. 7 The trajectory of the mass center of the rotor

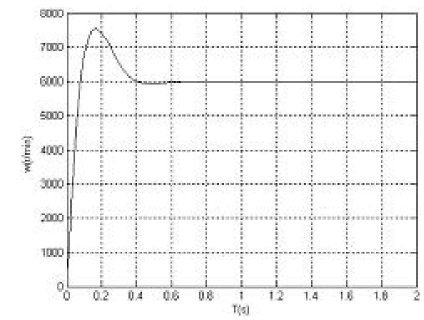

Fig. 8 Performance curve of the speed subsystem of bearingless induction motor

V. CONCLUSIONS

In this paper, the decoupling control arithmetic adopting α-th order inverse system theory has been educed. From research results, this strategy is succeed in realizing dynamic decoupling control between the radial displacement subsystems and speed subsystem of the 5 degrees of freedom bearingless induction motor. Not only each subsystems have been realized decoupling, but also all subsystems have been linearized and satisfy dynamic and static performance for this multivariable cross-coupling bearingless induction motor system.

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