Magnetic Force Compensation Methods in Bearingless Induction Motor

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Abstract: This paper presents magnetic suspension force control in bearingless induction motor. Simulation model of Vector controlled BLIM with MATLAB/SIMULINK and its response to reference forces are implemented. For improvement the response, PID controller is used and then for reduces the responce pulsation and eliminating its overshoot, POSICAST controller is applied to the system. The simulation results are compared with those obtained by the motor performance in previous models. The comparision confirms less system response pulsation and overshoot elimination than other metods.

Key words: Bearingless motor, induction motor, magnetic bearing, compensation force, vector control, posicast controller.

INTRODUCTION

Bearingless motors (BLM) are electro-magnetic devices which have a function of magnetic rotor levitation as conventional magnetic bearings. These electro-magnetics can be applied in super high speed drive applications such as turbo-molecular pumps, spindle drives, flywheels as well as pumps in harsh environments. One electro-magnetic unit of the bearingless drives provides radial forces in two-perpendicular axes as well as rotational torque. In order to provide both torque and radial forces, two sets of three-phase windings, i.e., two-pole windings and four-pole windings, are wound in the same stator slots (Akamatsu et al., 2005; Sugiki and Fututa, 2006). In the radial positioning of the bearingless motors, radial forces are generated based on the feedback signals of radial displacement sensors detecting the movements of the rotor shafts. The radial forces are generated taking advantage of the strong flux distribution of a revolving magnetic field in the air gap between the stator and rotor (Chiba et al., 1991). Currents in the suspension windings are regulated so that a rotor shaft can be successfully suspended in the center position by a negative feedback controller. Theoretically, in a stator, a combination of P-pole windings and (P ± 2)-pole windings generates a magnetic force (Okada et al., 1995). Practically, two-pole and four-pole motor windings are arranged with four-pole and two-pole suspension windings, respectively. Direct and indirect field-oriented controller for induction-type bearingless motors was proposed (Chiba et al., 1997). On the other hand a universal field-oriented controller was applied to realize perfect decoupling of radial forces in two perpendicular axes (Suzuki et al., 2000). Equivalent circuit of a bearingless induction motor (BLIM) and improved analysis of rotor flux linkages was presented in (Hiromi et al., 2007). In this paper, magnetic suspension force control in bearingless induction motor using posicast controller is shown.

In this paper, a bearingless induction motor with squirrel-cage rotor is proposed. The stator consists of four-pole main windings and two-pole control windings. The four-pole stator main windings are utilized to produce the driving torque of the induction motor. Also, the additional two-pole stator windings are used to create the magnetic bearing control forces.

Principle of Suspension Force Generation:

Fig. 1 shows the basic winding configuration of an BLIM. Two sets of three-phase windings are wound in the same stator slots. One is the two-pole windings for the production of motoring torque. It is called the motor winding. The other is the four-pole windings for controlling the rotor radial position in the air gap. This is referred as the radial force control winding. The four-pole flux $\lambda_2$ and two-pole flux $\lambda_y$ are generated by the winding currents $I_2$ and $I_y$ in the stator windings, respectively. $x$ and $y$ are the stationary perpendicular axes. Under no-load balanced condition, if positive suspension force along the $y$-axis is needed, the suspension winding current $I_y$ must be fed as shown in Fig. 1. The flux density in the upper airgap is increased, because both $\lambda_2$ and $\lambda_y$ fluxes are in the same direction. On the other hand, the flux density in the lower airgap is decreased because $\lambda_2$ and $\lambda_y$ are in opposite direction. A positive suspension force $F$ is produced in the $y$-axis.
direction only. The reverse current can produce the opposite suspension force. Suspension force in the x-axis direction can be produced using electrically perpendicular 4-pole current distribution using the same principle.

**Fig. 1:** Principles of suspension force generation

**Fig. 2:** Rotor displacement from stator center

Fig. 2 shows an expanded cross-sectional view of the air-gap area when a rotor center is displaced from the stator center position.

An estimation method of the displacement is based on the detected current variation with respect to the rotor displacements. The current variation is caused by the mutual inductance variations among two-pole motor windings and four-pole suspension windings. In order to verify that the mutual inductances are functions of the rotor displacement, theoretical expressions of mutual inductances was derived. The air-gap length function \( g(\phi) \) is related to a distance between the rotor outer surface and the stator inner surface (Chiba et al., 1994).

**Controller system block diagram:**

Fig. 3 shows the control system block diagram of proposed bearingless induction motor. The system equations and detailed expressions for the suspension force was derived for the squirrel-cage rotor bearingless induction motor in (Hiromi et al., 2007).

\[
\begin{align*}
\dot{1}_{2dg} &= \dot{1}_{2do} + \dot{1}_{2dq}, & \dot{1}_{2ag} &= \dot{1}_{2aq} + \dot{1}_{2ap} \\
\dot{1}_{4dg} &= \dot{1}_{4do} + \dot{1}_{4dq}, & \dot{1}_{4ag} &= \dot{1}_{4aq} + \dot{1}_{4ap}
\end{align*}
\]

(1)
The current amplitudes $i_{2_{ds}}$, $i_{2_{qs}}$, $i_{2_{dr}}$, $i_{2_{qr}}$, $i_{4_{ds}}$, $i_{4_{qs}}$, $i_{4_{dr}}$ and $i_{4_{qr}}$ are constant dc values in steady-state conditions. Moreover, $i_{2_{dg}}$ and $i_{2_{qg}}$ are current components of two-pole airgap flux and $i_{4_{dg}}$ and $i_{4_{qg}}$ are also current components of four-pole airgap flux. The suspension force is generated by an interaction of current components of two-pole and four-pole airgap fluxes (Hiromi et al., 2007).

$$
\begin{bmatrix}
F_x \\
F_y
\end{bmatrix} = M \begin{bmatrix}
i_{2_{dg}} & i_{2_{qg}} & i_{4_{dg}} \\
i_{2_{qg}} & i_{2_{dg}} & i_{4_{qg}}
\end{bmatrix}
$$

This equation provides us general suspension-force ($F_x$ and $F_y$) expressions for arbitrary instantaneous currents in both stator and rotor windings.

**Fig. 3:** Block diagram of BLIM control system

It is to be noted that the two-pole MMF wave traveling at the same velocity in space as the four-pole wave requires the synchronous electrical frequency of the two-pole current be one-half of the four-pole current. Fig. 4 shows waveforms obtained from numerical simulation.

Fig. 4(a) shows the $d$ and $q$-axis suspension forces, when the input $x$-axis suspension-force reference $F_x$ (=1 N) is changed as unit step. In ideal case, outputs $F_x$ and $F_y$ follow these commands $F_x$ and $F_y$. Fig. 4(b) shows airgap-flux component current waveforms.

**Fig. 4:** Force and currents in classic control

**Field oriented control of BLIM:**

Fig. 5 shows the block diagram of a field oriented control system of an airgap flux oriented vector controller system for the proposed bearingless induction motor. Generally, in the vector control system the flux is aligned with either the rotor or stator flux. In bearingless induction motors, the suspension force is produced by active unbalance of the airgap flux distribution between the rotor and stator. Therefore, electromagnetic force of magnetic suspension is originated from an interaction of the airgap fluxes. Thus, an airgap flux oriented vector control system is applied to bearingless induction motors (Akamatsu et al., 2005).
Employing air-gap flux-oriented vector controller, $i_{2qg}$ is zero. The $2 \times 2$ matrix in equation (2) is a diagonal matrix. As exciting current $i_{2dg}$ is kept constant, suspension forces are proportional to the four-pole stator winding currents $i_{4ds}$ and $i_{4qs}$ with the pole-specific rotor. Thus, the expressions for magnetic suspension force can be simplified. The shaft speed $\Omega_m$ is detected and speed errors are calculated. The error is amplified in a proportional-integral (PI) controller. The torque component current command $i^{*}_{qs}$ is generated. The superscript * indicates command values. A flux current component $i^{*}_{dm}$ is given as a constant. The d-axis current $i^{*}_{ds}$ and the slip angular frequency $\Omega_{se}$ are calculated from $i^{*}_{qs}$ and $i^{*}_{dm}$. If the command value $R^{*}_r$ of the rotor resistance is exactly the same as actual value $R_r$, then the airgap flux linkage is kept in a constant amplitude. In addition, the speed of the airgap flux linkage is $\Omega_0$, where $\Omega_0$ is a sum of $\Omega_{se}$ and the detected electrical rotor speed $\Omega_r$. In the controller for the suspension force as shown in Fig.5, radial positions x and y are detected by displacement sensors. These displacements are compared with the command values. The errors are amplified by proportional-integral-derivative (PID) controllers to generate the suspension force commands $F_x^*$ and $F_y^*$. Fig. 6 shows simulink results for field oriented controlled BLIM.

**Field oriented control of BLIM:**

By using a PID controller in the path of each force, we improve the ultimate value of the system’s response to reference forces up to an acceptable quantity. General scheme of applying the PID controller and its position in the control system is within fig. 7.

**Fig. 5:** Bearingless motor configuration with field oriented controller

**Fig. 6:** force and currents in field oriented control

**Fig. 7:** force compensation with PID controller
The response of the system, which has PID, to reference values of the force with similar instances parameters in the previous is showed in fig. 8. According to this figure, it is observed that the ultimate value of the response is so close the reference values, but from the viewpoint of the transient condition and overshoot and time duration to reach to steady state condition we have problem.

**Fig. 8:** force and currents of F.O.C. BLIM using PID controller

**Field oriented control of BLIM:**

Invented in the late 1950’s, Posicast is a feedforward control method that dampens oscillations in systems whose other transient specifications are otherwise acceptable. When properly tuned, the controlled system yields a transient response that has deadbeat nature. Consider a system having a lightly damped step response as shown in Fig. 9(a). The overshoot in the response can be described by two parameters. First, the time to the first peak is one half the underdamped response period $T_d$. Second, the peak value is described by $1 + d$, where $d$ is the normalized overshoot, which ranges from zero to one. Zero overshoot corresponds to critical damping. Posicast splits the original step input command into two parts, as illustrated in Fig. 9(b). The first part is a scaled step that causes the first peak of the oscillatory response to precisely meet the desired final value. The second part of the reshaped input is full scale and time-delayed to precisely cancel the remaining oscillatory response, thus causing the system output to stay at the desired value. Such is the idea behind “half-cycle Posicast,” which can be modeled using just the two parameters $d$ and $T_d$. The resulting system output is sketched in Fig. 9(c).

One block diagram interpretation of the half-cycle Posicast controller is shown in Fig. 10(a). The model has two forward paths. The upper path is that of the original, uncompensated command input. In the lower path, a portion of the original command is initially subtracted, so that the peak of the response will not overshoot the desired final value.

**Fig. 9(a):** A lightly damped transient response
Precisely a half cycle later, the command is fully restored to cancel oscillations and maintain the final value. The transfer function is given by the function $1 + P(s)$, where $P(s)$ is given by:

$$P(s) = \frac{d}{1 + d}(-1 + \exp(-\frac{T_d}{2}s))$$

Fig. 9(b): Posicast command

Fig. 9(c): System output

Fig. 10(a): Transfer function (P(s))

Fig. 10(b): Posicast within a feedback system
Classical Posicast generally suffers from sensitivity to modeling errors. The sensitivity problem can be reduced if Posicast compensation is applied within a feedback system rather than in the classical feedforward configuration (Chiba et al., 1991; 1991). A block diagram explaining the control method is shown in Fig. 10(b). Whereas the classical applications placed Posicast before the lightly damped system, recent work suggests that Posicast be used within a feedback system. The proposed control method is a significant departure from classical Posicast.

**Force compensation with POSICAST controller:**

Since the aim is controlling the suspension forces, \((1+P)s\) and \(C(s)\) are being put in the path of each force like Fig. 11. For each of forces, \(T_d\) and \(d\) parameters are counted independently and \(P(s)\) is being formed.

![Fig. 11: BLIM control with POSICAST](image)

The above parameters can be measured through Fig. 6; or we can identify the dominant poles by finding the transfer function of the system for two forces and obtain the parameters from them. In this paper, mentioned parameters have been obtained according Fig. 6.

\[
\begin{align*}
T_d &= 2.84 \text{ ms} \quad d = 0.252 \quad \text{for} \quad P_x(s): \\
T_d &= 0.12 \text{ ms} \quad d = 0.291 \quad \text{for} \quad P_y(s):
\end{align*}
\]

Consequences resulted from the above control have been indicated in Fig. 12.

![Fig. 12(a): A lightly damped transient response](image)

![Fig. 12(b): Posicast command](image)
Fig. 12 shows the efficiency of POSICAST control method in comparison with usual methods like PID controller.

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<thead>
<tr>
<th>Table 1: BLIM parameters used in this paper</th>
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<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>2-pole stator resistance</td>
</tr>
<tr>
<td>4-pole stator resistance</td>
</tr>
<tr>
<td>4-pole rotor resistance</td>
</tr>
<tr>
<td>2-pole rotor resistance</td>
</tr>
<tr>
<td>Stator winding self-inductance</td>
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<td>Stator winding self-inductance</td>
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<td>Stator winding self-inductance</td>
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<tr>
<td>2-pole stator mutual inductance</td>
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<tr>
<td>4-pole stator mutual inductance</td>
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<td>Mutual inductance between 2 and 4 pole windings</td>
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If we employ vector control to BLIM, it will be observed that suspension forces in x and y axis trouble with inconsistency and it will have much variation with the value of the reference force. By using PID controller, we can observe a better acceptable response, but it has mutation excess. By exact calculation the values of $T_d$ and $d$ and designing a suitable POSICAST controller in the path of the above forces, we can reduce the system's response oscillation and eliminate the overshoot it, and consequently reach to a suitable ultimate value in a shorter time.

REFERENCES


