DESIGN AND ANALYSIS OF BEARINGLESS PERMANENT MAGNET SYNCHRONOUS MOTOR

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ABSTRACT
Bearingless permanent magnet synchronous motor (BPMSM) has the characteristic of both conventional permanent magnet synchronous motor and traditional magnetic bearings. In this paper, the design and analysis of BPMSM by using Matlab/Simulink and ANSYS Maxwell are presented. The principle of electromagnetic force is utilized to ensure a stable levitation operation of BPMSM. The BPMSM mathematical model that has established to represent the dynamic of motoring force and radial suspension force is simulated in Matlab/Simulink environment. The ANSYS Maxwell, as an accurate finite element method (FEM) software in solving static, frequency-domain, and time-varying electromagnetic and electric fields is used to assist the development of BPMSM model before the integration with the control system is performed. The excitation of motoring winding and suspension winding are independently controlled through separate PI controller. The applications of BPMSM are suitable for high speed electrical machines such as compressors, turbines, pumps, and mixers.

Keywords: bearingless motor, self-bearing, permanent magnet synchronous motor, finite element method, mathematical model.

1. INTRODUCTION
Bearingless motor that has benefit of traditional magnetic bearing and conventional electric motor has been widely used in high speed machines [1]. The traditional magnetic bearing has excellent characteristic such as no mechanical contact, no physical friction, require no lubricant, and able to operate at higher speed can further increase the performances of permanent magnet synchronous motor. Bearingless motor was introduced for the first time in 1988 by R. Bosch. The terms of bearingless does not mean the lack of bearing forces but it means the missing of physical contact of the bearing component [2]. This missing bearing component allows the motor to become smaller in size and has a simple structure due to shorter rotor axial length caused by additional motor element installed in traditional magnetic bearing. Nowadays, various types of bearingless motor with embedded suspension winding to replace traditional magnetic bearing have been developed for induction motor, switch reluctance motors, brushless DC motor and PMSM. In this paper, BPMSM has been chosen due to its characteristic which is light weight, high torque density, high efficiency and reasonable production cost [3]. The designed BPMSM consist of two sets of stator winding namely motoring torque winding and suspension winding. The motoring winding alone with mechanical bearing is unable to hold the rotor at the center of rotation and this will cause the unstable operation due to unbalance magnetic force on the airgap. The unbalanced force is closely related to the rotor eccentricity. In order to maintain the rotor at the center of stator bore, the excitation of suspension winding is controlled through the algorithm of electromagnetic torque and radial suspension force [4].

The aim of the research is to establish the accurate mathematic model for BPMSM and later will be integrated with independent PI controller for both motoring forces and suspension force. The research covers on the principle of suspension force, BPMSM mathematical model, PI controller and FEM analysis. The structure of this paper starts with levitation principle, followed by bearingless control system and the simulation result. The last section concludes the paper and suggests future works for improvement.

2. SUSPENSION PRINCIPLE
Bearingless motor can be realized by generating an active controllable magnetic field in the airgap of the motor. To ensure the rotor is manageably suspended under the action of magnetic forces, the interaction of suspension force winding and torque winding with airgap magnetic field must be generated. As mentioned by Huangqiu Zhu [4], the generation of torque and suspension force at the same time is occurred when the torque winding and suspension force winding are placed in the same stator slots. In order to produce controllable suspension forces, the pole pairs relationship between torque winding and suspension winding should met the condition of $P_M = P_b \pm 1$, where $P_M$ and $P_b$ refer to pole pair number for torque winding and suspension winding respectively. Based on the Figure 1, the torque windings are $N_t$ and $N_b$ have a pole pairs of 2 respectively while $N_t$ and $N_b$ which are suspension force winding have a pole pairs of 1. When the rotor displacement is at the centre with no current flowing in $N_t$ and $N_b$, the resulting of symmetrical 4-pole flux $\Phi_p$ produced, flux...
density in each airgap is equal and no suspension force is produced. The rotor displacement at the negative direction of $x$-axis causes a positive Maxwell-Force to be generated to oppose the changes.

![Figure 1: Principle of radial force production [5]](image)

To ensure the rotor is in the centred position, the magnetic flux in area marks by 1 and 2 is regulated. The positive current of suspension winding $N_x$ will cause the 2-pole flux $\Omega_x$ is generated and flux density in airgap area 2 is increased while the flux in area 1 is decreased. To make the rotor returns to the central position, the negative direction force of $x$-axis must be produced. The same principle applied if the rotor is moving towards a negative $x$-axis which causes the current of suspension winding becomes negative. This idea of controlling the suspension force winding current of $N_x$ and $N_y$ in order to determine the direction and magnitude of radial forces [5] and [6] is utilized in this research.

In this case, 2-pole pairs number is chosen for torque winding and 1 pole pair’s number is chosen for suspension winding. The proposed BPMSM design is shown in Figure 2. The purple color rectangles are referring to torque winding while the red color rectangles are referring to suspension winding.

![Figure 2: FEM model of BPMS](image)

### 3. MATHEMATICAL MODEL

Based on electromagnetic field theory, when the rotor is not centered, the unbalanced radial force exists. The generate Maxwell-force, $F_{sx}$ and $F_{sy}$ will be experienced by the rotor [7]. This force is proportion to the off center displacement and the inherent forces which can be written as

$$
\begin{align*}
F_{sx} &= k_x x \\
F_{sy} &= k_y y
\end{align*}
$$

$k_x$ = force displacement coefficient

The equation for flux linkages and the current of suspension winding in (2) consists of 2-phase d-q axis components. $K_M$ and $K_L$ are Maxwell force and Lorentz force constant respectively while $\psi_d$ and $\psi_q$ are the airgap flux linkages.

$$
\begin{bmatrix}
F_{tx} \\
F_{ty}
\end{bmatrix} = (K_M \pm K_L) \begin{bmatrix}
\psi_d \\
\psi_q
\end{bmatrix} \begin{bmatrix}
i_d' \\
i_q'
\end{bmatrix}
$$

To obtain the required radial force in both $x$ and $y$ directions, the equation (1) and (2) are combined to produce radial suspension force as shown in (3).

$$
\begin{bmatrix}
F_x \\
F_y
\end{bmatrix} = (K_M + K_L) \begin{bmatrix}
\psi_d' \\
\psi_q'
\end{bmatrix} \begin{bmatrix}
i_d' \\
i_q'
\end{bmatrix} k_z
$$

The equation (3) is later expanded and written in matrix form that integrates the flux linkages and currents for both torque and suspension winding. $N_\alpha$ and $N_\beta$ such as shown in Figure 1 are defined as flux linkage of $\psi_d'$ and $\psi_q'$ while $N_\alpha$ and $N_\beta$ are defined as $\psi_d''$ and $\psi_q''$. The variable label as $L_m$ and $L_b$ are self-inductance for motor winding and suspension force winding respectively. $M'$ is mutual inductance whereas $i_d'$ and $i_q'$ are referring to $d$-axis component and $q$-axis component of suspension force winding’s current.

$$
\begin{bmatrix}
\psi_d' \\
\psi_q'
\end{bmatrix} = \begin{bmatrix}
L_m & 0 & M_x' & -M_y' & i_d' \\
0 & L_m & M_y' & M_x' & i_q'
\end{bmatrix}
$$

$$
M' = \frac{\pi \mu L_m N_\alpha N_\beta}{8} \frac{\tau - (L_m + L_b)}{(L_m + L_b)^2}
$$

$L_m$ = Length of rotor iron core

$L_b$ = Permanent magnet thickness

$L_g$ = Airgap length

$\mu$ = Magnetic conductance of air

$i_d'$ and $i_q'$ = Torque winding’s current at $\alpha-\beta$ axis

$i_d'$ and $i_q'$ = Suspension force winding’s current at $\alpha-\beta$ axis
The magnetic energy $W_m$ stored in the windings can be written as

$$W_m = \frac{1}{2} \mathbf{I}^T \mathbf{L} \mathbf{I}$$

where $\mathbf{I} = [i_a, i_d, i_q]^T$ and $\mathbf{L} = \begin{bmatrix} L_m & 0 & M'x \ M_x & L_M & M'y \ -M'y & M'_x & L_g \end{bmatrix}$

Later, the equation (4) and (5) are substituted into equation (6). By substituting $i_a = I_m \cos(2\omega t + \theta)$, $i_d = I_m \sin(2\omega t + \theta)$ and $I_m = \sqrt{i_d^2 + i_q^2}$, the result will be in equation (7). This equation shows the relationship between radial suspension force and suspension winding current.

$$\begin{bmatrix} F_x \\ F_y \end{bmatrix} = M \begin{bmatrix} \frac{\partial}{\partial x} \\ \frac{\partial}{\partial y} \end{bmatrix} \begin{bmatrix} i_A \\ i_B \end{bmatrix} = M' \begin{bmatrix} i_A \\ i_B \end{bmatrix}$$

The stator flux linkage for PMSM is shown as below

$$\Psi_d = L_d i_d + \Psi_r$$
$$\Psi_q = L_q i_q$$

where $\Psi_r$ is a rotor flux linkage produced by the permanent magnet. $L_d$ and $L_q$ are self inductance of motor windings.

The torque equation used in this research is the same for general PMSM. The equation is written in (10). The term $Tem$ is referring to electromagnetic torque, $J$ is moment of inertia and $P_1$ is pole pairs of torque windings.

$$T_{em} = P_1 (\left( \Psi_d i_q - \Psi_q i_d \right) = \frac{J}{P_1} \frac{\delta \omega}{\delta t} + T_L$$

4. CONTROL SYSTEM OF BPMSM

The design flow for the BPMSM is shown in Figure 3. The mathematical model for torque and suspension force is integrated with the control block diagram as shown in Figure 4. The subsystem for BPMSM is modelled by using the equation (3) and (9) while force to current transformation performed is based on the equation (7). The proportional integral (PI) controller will amplify the difference between the detected displacement and the demand values of $X^*$ and $y^*$. These allow the required radial suspension force, $F^*_X$ and $F^*_Y$ can be correctly determined. To achieve centre position, the value of $x^*$ and $y^*$ are set to 0.

![Figure 3: Design scheme](image)

5. FEM ANALYSIS

The Finite Element Method plays crucial part in assisting the development of BPMSM mathematical model. ANSYS Maxwell that considered as one of leading industrial standard finite element software are able accurately solving static, frequency-domain, and time-varying electromagnetic and electric fields. Figure 5 shows the surface mount permanent magnet which is designed by using two-dimensional finite element. It shows the flux distribution of BPMSM before and after the current is supplied to the torque and suspension winding. Figure 5(a) shows the flux lines is symmetrical and flux in each airgap is equally
distributed. However when the currents for suspension and torque are excited, the airgap fluxes become unbalanced as shown in Figure 5(b). The flux lines distribution shows an electromagnetic attraction is stronger at the left side compare to the right side. Figure 6 is magnetic field density in BPMSM in FEM.

Based on the level of magnetic field density, it shows the density is higher at the phase ‘a’ for suspension winding which at the left side of motor. This is because the current is supplied at phase ‘a’ suspension winding, sa and also at phase ‘a’ of torque winding, ma. The main parameters of BPMSM are shown in Table 1.

Table 1 Parameter of BPMSM

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius of stator inner surface</td>
<td>r_s</td>
<td>40 mm</td>
</tr>
<tr>
<td>Radius of rotor iron core</td>
<td>r_r</td>
<td>36.175 mm</td>
</tr>
<tr>
<td>PM thickness</td>
<td>l_m</td>
<td>2.93 mm</td>
</tr>
<tr>
<td>Airgap length</td>
<td>l_g</td>
<td>1 mm</td>
</tr>
<tr>
<td>Pole pair torque winding</td>
<td>P_M</td>
<td>2</td>
</tr>
<tr>
<td>Pole pair suspension winding</td>
<td>P_B</td>
<td>1</td>
</tr>
<tr>
<td>Motor winding</td>
<td>n_1</td>
<td>200</td>
</tr>
<tr>
<td>Suspension winding</td>
<td>n_2</td>
<td>200</td>
</tr>
</tbody>
</table>

6. SIMULATION RESULTS
The radial force results from FEM and Matlab are compared and tabulated in the Graph 1. The result shows that the comparison value for suspension force from FEM and Matlab is in the range of 4% to 18%.
Based on the block diagram in Figure 4, the demand displacement value is set to $x^*=0$ and $y^*=0$ and the result is shown in Figure 7. The parameter used for rated speed is 518 $\text{r/s}$, stator resistance is 0.07 $\Omega$, moment of inertia, $J$ is 0.0022 $\text{kg.m}^2$, stator inductances, $L_d$ and $L_q$ are 0.00597 $\text{H}$ and 0.00543 $\text{H}$ respectively and airgap 1mm. Initially, the rotor is unstable and the oscillation is higher but the motor is still in good condition and it seems that the rotor does not touch the inner stator. The displacement of rotor vibration is about 0.012859 $\mu\text{m}$ for $x$-axis and 0.004 $\mu\text{m}$ for $y$-axis.

Second test on the controller is done by setting the displacement demand value for $x^*$ and $y^*$ to 0.3mm. Result in Figure 8 shows that the rotor is oscillated at first and then maintains at 0.3mm position. The maximum value for this motor to oscillate is 0.045 $\mu\text{m}$.
7. CONCLUSION
This research is focusing on designing BPMSM which starts from derivation of its mathematical model for both radial suspension forces and motoring torque then followed by the integration with PI controller. The controller that independently control motoring winding and also suspension winding are able to achieve the stable operation. The experimental setup for this BPMSM will be performed later to further improve both model and control algorithm.

REFERENCES


