Bearing Capacitance Estimation of Electric Vehicle Driving Motor

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Abstract. The bearing capacitance and bearing voltage are the main causes of the failure of the driving motor bearing in the electric vehicle powered by the PWM inverter. It has an important influence on the driving safety of the electric vehicle, and is very important to calculate the bearing voltage and bearing current accurately. Taking 6006 ball bearings in 25KW permanent magnet motor as an example, this paper analyzes the load of each rolling element under the action of gravity, unilateral magnetic pull and centrifugal force. Then this paper discusses the effect of load distribution and speed on the contact area and oil film thickness between each rolling element and the raceway. And the estimation results of bearing capacitance at different speeds are given out. It could provide a reference basis for the life calculation and reliability analysis of the motor bearing in electric vehicle.

1. Introduction

As a new transportation to replace the traditional vehicle, the electric vehicle (EV) not only has the advantages of energy saving, high efficiency and green environmental protection, but also has the characteristics of safety, reliability and convenience of the traditional vehicle [1]. As an important part of the electric drive system in electric vehicles, the reliability of motors plays an important role in the driving safety of electric vehicles.

Bearing has always been one of components with the higher failure rate in the motor drive system. Most EV driving motor using inverter power, the common mode voltage of PWM driving system coupled to the motor shaft through the parasitic capacitances in motors, and formed the bearing voltage. When the rotor speed of the electric motor drive motor reaches more than 10% of the rated speed, the insulating oil film will be formed between the rolling element and the inner and outer raceway according to the theory of elastohydrodynamic lubrication (EHL). If the bearing voltage exceeds the breakdown value of the oil film, the electric discharge machining (EDM) current will be produced, which greatly reduces the life and reliability of the bearing [2]. Bearing capacitance affects not only the value of bearing voltage, but also the magnitude of EDM current [3]. The film thickness also has a great effect on breakdown threshold voltage of oil film; therefore, it is necessary for in-depth analysis of the bearing capacitance.
Based on the special structure of the electric drive system in electric vehicle, the zero sequence current loop of the motor system is set up. The influence of the velocity and load distribution on the contact area of the rolling element and the raceway and the thickness of the central oil film is given, and the equivalent of the electric motor bearing capacity is built. The simplified model is given out in order to estimate the bearing capacitance of EV under certain load distribution and different speed.

2. Bearing Voltage Model
The capacitances between the rolling elements and the inner and outer raceways are in series. Due to the large distance between the inner/outer raceways, the equivalent capacitance between the inner/outer raceways is small. The distance between the inner/outer race of the bearing cage and the bearing is relatively large, and the relative area is small, resulting in a smaller value of equivalent capacitance. Therefore, this paper ignores the influence of the bearing cage on the bearing raceway and the capacitance between the inner/outer raceways.

Based on the reference [4], the CM equivalent circuit of EV motor drive system is shown as figure 1.

Figure 1. The common mode circuit

In figure 1, $Z_0$ is zero sequence impedance of the three-phase winding; $o'$ and $o$ are middle point of DC side and equivalent midpoint of three-phase winding in motor respectively; $g$ represents vehicle body; the capital letter $C$ is abbreviation of capacitance and the subscript $r$, $s$, $f$, $b$ represent rotor, stator winding, stator core, and bearing; $C_\Delta$ is the parasitic capacitance of the reducer and other drive systems, $C_{in}$ is the capacitance between positive/negative polar and vehicle body. By analyzing the equivalent circuit in figure 1, the bearing voltage $v_{bg}$ is related to the CM voltage $v_{oo'}$ and parasitic capacitance of the common mode loop.

The bearing to the body voltage $v_{bg}$ and the midpoint of the winding to the body voltage $v_{og}$ satisfy

$$\frac{v_{bg}}{v_{og}} = \frac{C_{sr}}{C_{rf} + 2C_b + C_\Delta + C_{sr}}$$  \hfill (1)

As shown in the equation (1), the common mode voltage is the most influential factor of bearing voltage. Higher CM voltage would couple to a larger bearing voltage, and the amplitude of the discharge current will increases, so the bearing life will be reduce. The parameters such as capacitance between the rotor and stator windings also have a certain influence on the bearing voltage.

$v_{og}$ and $v_{oo'}$ satisfy the following relations

$$\frac{v_{bg}}{v_{oo'}} = \frac{C_{in}}{C_{og} + C_{in}}$$  \hfill (2)

Where $C_{og}=C_d/[C_{sr} + (C_d/2C_b/C_\Delta)]$.

Through the special structure of EV as well as the theoretical analysis, it is found that $C_{in}$ value is large because of using of super capacitors or battery as a power source of EV leads to requiring a large number of capacitors or batteries in series or parallel, and the limited space in EV also leads to the
small distance of positive and negative polar and vehicle body. Generally $C_{in}$ is up to about 10 times $C_{ov}$, and it can be obtained $v_{ov}=v_{ov'}$, so Eq(1) can be used to analyze $v_{ov}$ and $v_{ov'}$.

The value of $C_{sr}$ and $C_{rf}$ can be calculated with plate capacitor theory, no further explanation has been given in this section. And the value of $C_{b}$ and $C_{A}$ will be analyzed in the next section.

3. Bearing Capacitance Analysis

3.1. Rolling Element Load Distribution

When the electric vehicle motor rotates, the contact areas between the rolling elements and the raceway and the thickness of the oil film have a significant influence on the capacitance of the bearing. The above two factors are related to the load of rolling elements and raceways. In this paper, the pseudo-dynamics are used to simulate the bearing load.

A 6006 ball bearing in 25 kW PM is used as example. The radial load related to bearing is consisted of the rotor gravity, centrifugal force and unilateral magnetic pull. In the analysis of the load on each rolling element, assuming the contact angle $\alpha = 0$.

For ball bearings, when speed is below a certain level, the radial load that acting on the ball has two parts, one is the rotor gravity and the other is the unilateral magnetic pull $F_M0$. $F_{M0}$ is given by

$$F_{M0}=\beta\pi D ef e_0 B_2 \delta/2 \delta \mu_0$$

Where $\beta$ is the experience coefficient of the PM motor, $D$ is the stator inner circle diameter, $ef$ is the effective length of the stator winding, $\delta$ is average gap length, $e_0=0.1\delta$ is eccentricity, $\mu_0$ is the vacuum magnetic permeability and $B_2$ is the flux density.

When unilateral magnetic pull is in the same direction of gravity, the bear load of bearing is the maximum, as shown in figure 2.

![Figure 2. Gravity and magnetic pull](image)

Considering the maximum load, this paper analyzes the load of the ball in the different regions. The ball $A1$ bears the maximum load, the maximum load can be calculated with the expression:

$$Q_{max}=5(F_{M0}+G)/11 \cos \alpha$$

The ball bearing load $Q_{\sigma}$ located at position angle $\sigma$ is given by

$$Q_{\sigma}=Q_{max}[1-0.5x(1-\cos \sigma)]^{1.5}$$

Where $x$ is load distribution factor.

The centrifugal force $F_l$ of the rolling elements is given by

$$F_l=0.262 \rho D^3 D_{pw}(2\pi n/60)^2$$

Where $\rho$ is steel density, $D$ is the diameter of rolling element, $D_{pw}$ is bearing pitch circle diameter and $n$ is speed.

The load distribution of ball in 6006 bearing can be calculated with equation 3~ equation 6.

3.2. Hertzian Contact Area Analysis
The ellipse Hertzian contact area is one of the important factors affecting bearing capacitance, and the major and minor axis of between ball and inner/outer raceway are given in [5] as following

\[ x_{i/o} = x^* \left[ \frac{3Q}{2} \sum y_{i/o} \left( \frac{1-\mu_i^2}{E_i} + \frac{1-\mu_o^2}{E_o} \right) \right]^{\frac{1}{2}} \]  \hspace{1cm} (7)

Where \( Q \) is load, \( E_1, E_2 \) and \( \mu_1, \mu_2 \) respectively are elastic modulus and Poisson's ratio of ball and raceway, \( x \) is major and minor radius of ellipse, \( x^* \) are dimensionless parameter, \( y \) is the principal curvatures of inner/outer raceway, subscripts \( i \) represents inner raceway and \( o \) represents outer raceway.

The Hertzian contact area can be calculated by the formula of ellipse area, and simulated in figure 3.

3.3. Minimum Film Thickness Analysis

The film thickness is given in [6]

\[ h = 2.69 \cdot G^{0.53} \cdot U^{-0.67} \cdot W^{-0.067} \cdot (1-0.36e^{-0.73k}) R_x \]  \hspace{1cm} (8)

Where, the material parameters \( G' \) is the function of viscosity pressure coefficient \( \alpha \) and the elastic modulus \( E' \), \( G' = \alpha E' \), the speed parameter \( U' \) is the function of the oil viscosity \( \eta_0 \), the rolling average speed \( U \), the effective radius \( R \), and \( E' = \eta_0 U/E' R_x \), the load parameter \( W' \) is a function of bearing radial load \( W \), the number of rolling elements \( Z \) and \( R_x \), \( W' = W/ E' R_x^2 \), \( 1-0.36e^{-0.73k} \) is the impact factor of bearing side vent, the ellipticity \( k = 1.03(R_y/R_x)^{0.64} \).

The factors impacting film thickness are various, and speed has a great effect on film thickness. Simulation is carried out based on a SIMULINK model, and \( h_{1b}, h_{2b} \) respectively are the film thickness of the ball and inner/outer raceway. According to figure 2, the results of \( h_{1b}, h_{2b} \) are given in figure 4.

In figure 4 the film thickness varies within 0.1-1 um at different speeds. The film thickness increases with increasing speed, and the film thickness decreases with increasing load at the same speed.
3.4. Bearing Capacitance Estimation

The capacitances between each of the rolling elements and the inner/outer raceway are series, ignoring the importance of raceway and rolling element. The value of $C_{A1}$, $C_{A2}$, $C_{A3}$, $C_{A4}$ represent the capacitances ($C_i$, $C_o$ in figure 2) are shown in figure 5.

Figure 5. Balls capacitances

In figure 5 the capacitors decrease with increasing speed and decreasing load under the same speed. The bearing load of the rolling element $A$ is much larger than that of $A1$, resulting that the film thickness of $A$ is much smaller than that of $A1$, so $C_{A1}$ is much larger than $C_A$. With this conclusion, the value of $C_A$ is derived as follows: reducer is generally constituted by the bearings and gears, based on the special structure of EV, radial loads act mainly on the motor bearings, the smaller radial loads of reducer will cause that the film thickness is larger and the value of $C_A$ is smaller. To simplify the analysis process, the effect of $C_A$ on shaft voltage is ignored in this paper.

The grease thickness and spatial distribution of bearing ball are different as EV traveling, so that the capacitances of the inner/outer raceway and balls are not constant but varies with the motor shaft speed and load. In the speed range considered, the capacitance between balls and the inner/outer raceway directly under the load zone have maximum value.

4. Conclusions

Considering the gravity of the rotor, unilateral magnetic force and the centrifugal force, the load distribution and film thickness of each bearing ball that of drive motor bearing in EV are given out. As the driving motor bearing under maximum load, the values of the bearing capacitance are estimated for the EV driving motor at different speeds.

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