Research and Analysis of Electromagnetic Thrust of Variable Pole Distance Linear Induction Motor

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Abstract. According to the actual acceleration index requirements, a high-speed large-thrust linear induction motor for accelerating the system was designed. Due to the variable pole pitch design, the variation of the pole pitch plays a key role in the design, and the influence of the variation of the pole pitch on the output of the electromagnetic thrust is analyzed. The variable pole distance double-sided linear induction motor is used as the acceleration drive. It does not need to detect the speed and displacement. The primary winding current frequency is constant. As the speed increases, it will not be limited by the inverter frequency, and will not increase the motor loss. The frequency is constant and the control is optimized and simpler.

1. Introduction

The air gap flux density of the long primary bilateral linear induction motor consists of a forward basic traveling wave, a forward inward traveling wave, and a reverse outgoing traveling wave. The pre-wave magnetic field exists only at the secondary input end, the backward traveling wave magnetic field exists only at the secondary output end, and the combined magnetic field of the secondary intermediate segment portion is mainly composed of the basic traveling wave magnetic field.

At present, the traditional fixed-pole double-sided linear induction motor with fixed pole moment is used as the acceleration ejection. The coil winding frequency control electromagnetic thrust output needs to be changed, and the closed-loop feedback control method is adopted to continuously detect the speed or the ejection displacement to ensure the specified distance. The ejection task is completed within. The entire ejection process is short and the control is difficult. Moreover, as the speed increases, the current frequency of the motor increases continuously, and the inverter frequency must be limited. The increase of the current frequency at high speed causes the motor loss to increase.

Therefore, the structure of the primary and double-sided linear induction motor with variable pole length is proposed. When the initial design and manufacture of the motor is used, the CNC machine tool is used for machining. At different displacements, the pole width of the motor can be different. As shown in Figure 1.
The motor adopts a slotless winding structure, and the load is uniformly accelerated under the condition of constant voltage and constant frequency power supply. Keeping the other structure and design parameters of the motor constant, and the current frequency is constant, the pole pitch of the motor gradually increases with the increase of the speed. The change of the polar moment will undoubtedly affect the surface current, the quality factor, the magnetic field strength and other parameters, and thus affect the motor magnetic field. Analyze the magnetic field of the variable-pole-length primary bilateral linear induction motor to rationalize the design parameters and ensure that the ejection acceleration task is completed within the specified length of time.

2. Air gap magnetic field analysis
An ideal model for establishing a long primary bilateral linear induction motor is shown in Figure 2. When analyzing a long primary bilateral linear induction motor, it is assumed that the primary infinite length is divided into three regions according to the primary coverage of the secondary region, and the region I \((0<x<2p\tau)\) and the region II \((-\infty<x<0)\), region III \((2p\tau<x<\infty)\), where region I is the secondary coverage effective region, and region II and region III are the invalid regions. The traveling wave magnetic field generated by the current layer moves along the positive direction of the x-axis at a synchronous speed \(v_s\). Under the action of the traveling wave magnetic field, an induced eddy current is generated in the secondary conductive plate, and the generated eddy current interacts with the traveling wave magnetic field to generate an electromagnetic thrust output. The secondary conductive plate moves in the positive direction of the x-axis at a speed \(v_x\) under the action of electromagnetic thrust.

Assumption:
(1) The primary core magnetic permeability \(\mu_{Fe}\) is infinitely large, and the \(\sigma_{Fe}\) conductivity is zero, that is, the primary core loss is ignored;
(2) The primary core and windings are infinitely long and extend along the y-axis to infinity;
(3) The air gap magnetic fields \(H\) and \(B\) have only the y-axis component;
(4) The primary and secondary currents \(j_1, j_2,\) and \(E\) have only z-axis components;
(5) Each field quantity is only a function of the spatial position \(x\) and only varies sinusoidally with time \(t\).

(6) Core saturation, hysteresis loss and skin effect of secondary conductors are negligible.

When the positive direction of the current layer is the positive direction of the coordinate \(z\)-axis, the upper and lower primary synthetic equivalent traveling wave current layers are

\[ j_1 = J_1 e^{j(\omega t - \beta x)} \]  

(1)

Where \(J_1\) - traveling wave current layer amplitude; \(\omega\) - current angular frequency, \(\omega = 2\pi f\); \(v\) - harmonic order, since only the \(j_1\) fundamental component is considered, \(v = 1\); \(\beta\) - the length of each pole corresponds to the electrical angle, \(\beta = \pi/\tau\); \(\tau\) — the pole pitch of the motor.

The traveling wave magnetomotive force and the equivalent traveling wave current layer amplitude generated by the primary winding current are respectively

\[ A = \frac{\sqrt{2} k_{m1} m_1 \sigma_1 I_1}{\pi p} e^{j(\omega t - \beta x - \pi / 2)} \]  

(2)

\[ J_1 = \frac{\sqrt{2} k_{m1} m_1 \sigma_1}{p \tau} I_1 \]  

(3)

Where \(k_{m1}\) - primary fundamental winding coefficient; \(m_1\) - primary winding phase number; \(\sigma_1\) - primary winding per phase series turns; \(I_1\) - primary phase current effective value; \(p\) - secondary corresponding primary winding pole pairs.

According to Ampere's theorem and Faraday's law of electromagnetic induction, the second-order constant coefficient non-homogeneous linear differential equations for the air gap magnetic field density \(B_{\delta l}\) in the effective region \(I\) are obtained.

\[ B_{\delta l} = B_{\delta l0} + B_{\delta l1} + B_{\delta l2} = B_{\delta m} e^{j\beta s} e^{j(\omega t - \beta x)} + C_1 e^{\frac{x}{m_1}} e^{j\left(\omega t - \beta x - \pi / 2\right)} + C_2 e^{\frac{x}{m_2}} e^{j\left(\omega t - \beta x + \pi / 2\right)} \]  

(4)

The coefficients \(m_1, m_2, m_3\) are:

\[ m_1 = \frac{2}{k_1 (-1 + 0.7 \sqrt{1 + k_2})} \]  

(5)

\[ m_2 = \frac{2}{k_1 (1 + 0.7 \sqrt{1 + k_2})} \]  

(6)

\[ m_3 = \frac{2\pi}{0.7 k_1 \sqrt{-1 + k_2}} \]  

(7)

The coefficients \(k_1\) and \(k_2\) in the formula are:

\[ k_1 = G \beta \left(1 - s\right) \]  

(8)
\[
k_2 = \sqrt{1 + \left(\frac{4}{G(1-s)^2}\right)^2}
\]

Where \(s\) - slip rate; \(G\) - quality factor.

The coefficient \(B_{\delta m}\) is:

\[
B_{\delta m} = \mu_0 J m \delta^{-1} \beta^{-1} \left[1 + (sG)^2\right]^{-\frac{1}{2}}
\]

According to the air gap magnetic field density expression, in the air gap magnetic field of the long primary bilateral linear induction motor, both the un-attenuated pre-wave magnetic field and the forward and backward two-way attenuation magnetic field due to the end effect are included. They are superimposed on the front wave magnetic field, causing the synthetic magnetic field to be distorted.

By the continuity of the magnetic flux density of the region I, the region II, and the region III, the complex constants \(C_1, C_2\) in the equation (4) can be solved.

\[
\begin{align*}
C_1 & = \frac{\mu_0 s G J m_1 (1 - e^{M_1})}{\beta \delta \varepsilon (1 + jsG) (-e^{-M_1} + e^{M_2})} \\
C_2 & = \frac{\mu_0 s G J m_1 (-1 + e^{-M_1})}{\beta \delta \varepsilon (1 + jsG) (-e^{-M_1} + e^{M_2})}
\end{align*}
\]

The coefficients \(M_1\) and \(M_2\) in the formula are:

\[
\begin{align*}
M_1 & = 2 \pi \tau \left(\frac{1}{m_1} + j \frac{\pi}{m_3}\right) \\
M_2 & = 2 \pi \tau \left(\frac{1}{m_2} + j \frac{\pi}{m_3}\right)
\end{align*}
\]

According to the expression analysis, the front wave magnetic field and the backward traveling wave magnetic field caused by the end effect have nearly the same amplitude and attenuate in the opposite direction of the coordinate axis at the same speed.

3. Motor electromagnetic thrust output calculation

The electromagnetic thrust equation of the long primary bilateral linear induction motor is based on the analysis of the magnetic gap flux density of the motor. According to the Lorentz force formula, the instantaneous thrust is calculated in the effective area of the secondary coverage. Since the air gap flux density of the motor is composed of the forward basic traveling wave flux density \(B_{00}\), the forward entering traveling wave flux density \(B_{01}\), and the reverse outgoing traveling wave flux density \(B_{02}\), the linear induction motor electromagnetic thrust It is also composed of three parts, namely, the forward basic traveling wave thrust \(F_{e0}\), the forward inward traveling wave thrust \(F_{e1}\), and the reverse outgoing traveling wave thrust \(F_{e2}\).

\[
F_e = F_{e0} + F_{e1} + F_{e2} = 2 \times 2 \pi \times \frac{1}{2} \int_{\theta_0}^{\theta_1} (j^1 B_\theta) d\theta
\]
Where \(2a\) - primary core width; \(L\) - secondary guide length, \(L=2\pi r\); \(j_1^*\) - conjugate complex number of primary current density vector \(j_1\).

The expressions for each thrust component are each:

\[
F_{e0} = 2a \cdot 2\pi \cdot \frac{1}{2} \int_{-\delta}^{\delta} j_1 B_0 \, \cos(\theta) \, dk = 2aL_0 \int_{-\delta}^{\delta} B_0 \cos(\theta) \, dk \tag{16}
\]

\[
F_{e1} = 2a \cdot 2\pi \cdot \frac{1}{2} \int_{-\delta}^{\delta} j_1 B_0 \, \cos(\theta) \, dk = 2aL_0 \int_{-\delta}^{\delta} B_0 \cos(\theta) \, dk \tag{17}
\]

\[
F_{e2} = 2a \cdot 2\pi \cdot \frac{1}{2} \int_{-\delta}^{\delta} j_1 B_0 \, \cos(\theta) \, dk = 2aL_0 \int_{-\delta}^{\delta} B_0 \cos(\theta) \, dk \tag{18}
\]

In the formula, the magnetic density amplitudes \(B_0\), \(B_1\), and \(B_2\) are:

\[
B_0 = \frac{\mu_0 J_1}{\delta \beta \sqrt{1+(sG)^2}}
\]

\[
B_1 = C_1 e^{\frac{k_1(1-0.7)(1+k_2)\beta}{2}}
\]

\[
B_2 = C_2 e^{\frac{k_2(1+0.7)(1+k_2)\beta}{2}}
\]

The phase angles \(\theta_0\), \(\theta_1\), and \(\theta_2\) are:

\[
\theta_0 = -\beta x + \tan^{-1}\left(\frac{1}{sG}\right)
\]

\[
\theta_1 = -\frac{\pi x}{m_3} + \tan^{-1}\left[\frac{\text{Im}(C_1)}{\text{Re}(C_1)}\right]
\]

\[
\theta_2 = \frac{\pi x}{m_3} + \tan^{-1}\left[\frac{\text{Im}(C_2)}{\text{Re}(C_2)}\right]
\]

When the influence of the end effect on the air gap magnetic field is not considered, only the normal traveling wave thrust is analyzed, and the integral solution of the equation (26) can be obtained.

\[
F_{e0} = 2aL_0 \int_{-\delta}^{\delta} B_0 \cos(\theta) \, dk = \frac{\mu_0 J_1}{\delta \beta \sqrt{1+(sG)^2}} \cdot \frac{LsG}{\sqrt{1+(sG)^2}}
\]

The extremum of equation (35) is obtained. When the slip rate is \(s=1/G\), the normal traveling wave thrust reaches the maximum value.

\[
F_{e0\max} = \frac{a\mu_0 L^2 J_1^2}{\delta \beta}
\]
4. Analysis of electromagnetic thrust output characteristics

In order to study and analyze the influence of various design parameters of the variable-pole linear induction motor on the output of electromagnetic thrust, the design parameters of a long primary bilateral linear induction motor with a maximum speed of up to 100m/s were selected for modeling and simulation analysis. The basic parameters are shown in Table 1.

| Parameter                        | Value  | Parameter                        | Value  |
|----------------------------------|--------|----------------------------------|--------|
| Line current rating \( I_N \) / KA | 15     | Current frequency rating \( f_N \) / Hz | 300    |
| Line voltage rating \( U_N \) / KV | 10     | Secondary pole logarithm \( p \) | 6      |
| Primary winding phase number \( m \) | 3      | Number of turns per phase \( \varpi \) | 8      |
| Angular frequency \( \omega \) / rad/s | 1.8*10^3 | Motor rated pole pitch \( \tau \) / m | 0.30   |
| Primary core width \( 2a \) / m | 1.5    | Primary core height \( h_s \) / m | 0.2    |

Without considering the influence of the end effect on the air gap magnetic field, the characteristics of the electromagnetic thrust generated by the normal traveling wave thrust and the motor design parameters are analyzed, and the primary core width \( 2a \), the motor pole distance \( \tau \), and the equivalent air gap length \( 2\delta_e \) are analyzed. The effects of the primary phase current frequency \( f \), the secondary thickness \( 2d \) and the electrical conductivity \( \sigma \) on the electromagnetic thrust output are shown in Figures 3-8, respectively.

When the constant current source is guaranteed to supply power, the electromagnetic thrust \( F_{e0} \) increases with the increase of the motor speed under different design parameters. When the speed is small, the electromagnetic thrust output is small, that is, the starting thrust of the motor is relatively small. It can be known from equation (35) that the primary core width \( 2a \) and the electromagnetic thrust are approximately proportional, and the change of the motor pole distance \( \tau \) not only affects the slip frequency \( s \), but also the quality factor \( G \), and also affects the traveling wave current layer amplitude \( J_1 \). As the width of the primary core increases, the pole pitch of the motor decreases and the electromagnetic thrust increases.

**Figure 3.** Electromagnetic thrust curve for different primary core widths.

**Figure 4.** Electromagnetic thrust curve of different motor pole pitch.
It can be clearly seen from the analysis of the electromagnetic thrust expression that the equivalent air gap length $\delta_e$ is inversely proportional to the basic traveling wave electromagnetic thrust. As the equivalent air gap length increases, the electromagnetic thrust output decreases. The secondary thickness $2d$ and the secondary conductivity $\sigma$ mainly affect the motor quality factor. The change of the power supply frequency $f$ mainly affects the quality factor and the slip rate, and the output of the electromagnetic thrust increases with the decrease of the design value. Appropriate changes in design parameters within the design allowable range can increase the output of the electromagnetic thrust.

![Figure 5. Electromagnetic thrust curve with different equivalent air gap length.](image1)

![Figure 6. Electromagnetic thrust curve at different power supply frequencies.](image2)

![Figure 7. Electromagnetic thrust curve at different secondary thicknesses.](image3)

![Figure 8. Electromagnetic thrust curve with different secondary conductivity.](image4)

When the slip ratio $s=1/G$, the normal traveling wave thrust reaches the maximum value, and it can be known from equation (36) that the output of the maximum electromagnetic thrust is only $2a$ with the primary core width, $\sigma$ for each phase, and the equivalent air gap length is inversely related. The primary core width, the number of turns per phase, and the maximum thrust output are proportional to each other. As the value increases, the maximum thrust output increases. The equivalent air gap length is inversely proportional to the maximum thrust output. While ensuring the normal operation and efficiency of the motor, the higher the speed at which the maximum thrust point is reached, the better the selection of appropriate parameters can increase the maximum electromagnetic thrust output.
5. Conclusion
The structure of the pole-to-length and long-term primary double-sided linear induction motor only needs to be in the initial design and manufacture of the motor. The distance between the motor and the motor can be changed at different displacements. The pole pitch of the motor can be continuously changed, and can be changed in stages. The manufacturing process can be adopted. CNC machine tools are easy to process. The variable pole distance double-sided linear induction motor is used as the ejection drive. It does not need to detect the speed and displacement. The primary winding current and current frequency are constant. As the speed of the accelerated object increases, it will not be limited by the inverter frequency. Increased motor losses, control mode is optimized and simpler due to constant current frequency.

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