Electromagnetic Design of Toroidal Permanent Magnet Linear Synchronous Motor

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ABSTRACT For the permanent magnet linear synchronous motors (PMLSM) with high-speed and large-thrust under the periodic transient conditions, the corresponding length and cost requirements are large. This paper designs a toroidal long primary PMLSM. In order to analyze the characteristics of the motor, the expressions of the electromagnetic force and the air-gap magnetic flux density are derived, then the finite element comparison analysis is performed for the linear structure and the toroidal structure of the PMLSM. The results indicate that the space occupied by the toroidal structure is reduced greatly under the same performance index, the required power level has obvious advantages, and the acceleration and braking time are not limited by the stroke. The structure of toroidal PMLSM is further optimized so as to suppress the thrust fluctuation, the comparison of air-gap flux density and electromagnetic force finite element simulation results verifies the validity of the structural optimization.

INDEX TERMS TPMLSM, electromagnetic design, electromagnetic thrust, thrust ripple, structure optimization.

I. INTRODUCTION
Linear induction motors (LIM) are often applied in high-speed and large-load transportation situations such as automobile accelerated collision tests [1], but it has shortcomings such as low power factors, low efficiency, large primary current, complex feeding for high-speed and long-stroke occasions and low thrust density. Compared with LIM, PMLSM has the benefits of small size, high efficiency, large thrust density, high positioning accuracy, unlimited travel, low noise, which is mostly used in places that require high accuracy or performances such as transportation and vertical lift system [2]. At present, there are few researches on PMLSM under transient conditions, the related research is limited to low-speed, high-precision and short-stroke applications [3], [4]. Therefore, it is necessary to conduct in-depth research on PMLSM under high-speed and large-thrust period transient conditions. Reference [5] introduced two kinds of LIM and PMLSM for Electromagnetic Launch (EML) system, it is concluded that PMLSM is more suitable for EML in terms of power factor through theoretical calculation and finite element analysis. A multi-layer structured PMLSM is proposed in [6], [7], which improves the motor thrust density while reducing thrust ripples by optimizing the motor winding and permanent magnet structure. References [8], [9] proposed two double-sided PMLSM with ring windings structure and studied its characteristics through theoretical analysis and numerical calculation, and concluded that the ring windings is more suitable for PMLSM in EML. The thrust characteristics of double-sided PMLSM with quasi-sinusoidal ring winding are analyzed in [10]. The electromagnetic force of bilateral PMLSM under different occasions are analyzed in [11]. Reference [12] optimizes the permanent magnet length, permanent magnet group shifting length and slotting opening length of PMLSM through the response surface method (RSM) to weaken the detent force.

This paper proposes a Toroidal PMLSM(TPMLSM) for high-speed and large-thrust under periodic transient conditions, its performance is analyzed theoretically and verified by finite element analysis, meanwhile, it is compatible with the corresponding long primary PMLSM, and it was concluded that the toroidal long primary PMLSM has better electromagnetic performance. Finally, the structure optimization and electromagnetic performance comparison analysis are carried out.

II. MOTOR STRUCTURE DESIGN
The structure of long primary double-sided PMLSM is presented in Fig.1, the primary core is laminated by double-side
slotted silicon sheet sheets, which is equivalent to two single-side slotted cores placed back-to-back. The ring windings is excited by three-phase symmetric current to generate air-gap traveling wave, which generates electromagnetic force by interacting with the field produced by the permanent magnet. In addition, the permanent magnet is separated from the back iron and the fixed back iron is adopted, which reduces the mass of the secondary and improves the dynamic performance and emission efficiency.

![FIGURE 1. Bilateral long primary PMLSM structure.](image1)

The kinematic analysis shows that the movement stroke required to achieve high-speed operation is long under periodic transient conditions, the long primary PMLSM requires more space and higher cost for practical applications, therefore, a toroidal long primary PMLSM structure is proposed as presented in Fig.2 so as to realize the unlimited time and distance of acceleration and braking, which saves space and reduces costs while achieving the same performance as the linear structure.

![FIGURE 2. Toroidal bilateral long primary PMLSM structure.](image2)

The structural parameters of the toroidal long primary PMLSM are the same as linear structure, but the toroidal structure has some special design as follows, taking the convenience of connecting the shaft and the counterweight into account, the permanent magnet of the secondary is divided into two sections with a mutual difference of 180° in space, each section has two poles. A rotating shaft is set in the center of the motor, and the two permanent magnets are connected through the connecting plate on the rotating shaft. The connecting plate not only plays the role of fixing the permanent magnets, but also offsets part of the normal force. When the motor fails at high speed, the connecting plate can prevent the permanent magnets from flying out, in addition, a resolver can be installed on the shaft to detect the speed of the secondary, which is convenient for control, and the entire motor is supported and fixed by the bearing plate.

### III. THRUST ANALYSIS OF LONG PRIMARY PMLSM

#### A. THEORETICAL MODEL

In the theoretical analysis of electromagnetic field, quasi-one-dimensional field and two-dimensional field are the main methods to analyze specific problems of linear motors, the higher the dimension of the field, the more accurate the calculation result, but the more complicated the solution process [12]. The spatial field and current distribution of the long primary PMLSM is a three-dimensional field, but after some simplified assumptions, two-dimensional field analysis can be used to obtain an analytical solution that is convenient for practical applications. The PMLSM structural model is presented in Fig.3.

![FIGURE 3. PMLSM structure model.](image3)

As illustrated in Fig.3, $L_1$ represents the primary length, $h_1$ represents the primary height, $h_0$ represents the slot height, $b_0$ denotes the slot width, $\delta$ denotes the air gap thickness, $b_t$ denotes the tooth width, $t$ indicates the slot pitch, $b_m$ indicates the permanent magnet length, and $\tau$ is the pole pitch, $h_m$ represents the permanent magnet height, $h_2$ represents the height of the back iron of the secondary.

The basic assumptions are as follows: 1) The primary and secondary are isotropic, and the permeability is infinite; 2) The permanent magnet material is radially and uniformly magnetized Nd-Fe-B, whose returning curve is identical with the demagnetization curve. There is no magnetic leakage between poles and magnetic permeability in the x-direction and y-direction are equal to the permeability of air; 3) There
is no change in the magnetic field along the z-axis, and the current only has a component in the z-direction.

**B. AIR-GAP MAGNETIC FIELD DERIVATION**

The basic equation of electromagnetic field used for PMLSM theoretical analysis is

\[
\begin{align*}
\nabla \times H &= J \\
\nabla \times E &= -\frac{\partial B}{\partial t} \\
\n\nabla \cdot B &= 0 \\
\end{align*}
\]

(1)

Among them, \( H \) represents the magnetic field intensity, \( B \) represents the magnetic field density, \( E \) denotes the electric field intensity, and \( J \) denotes the current density.

Since the excitation of the air-gap field is made up of two parts: the windings and the permanent magnet of the secondary, the equivalent current sheet theory and the equivalent magnetizing current theory are applied to analyze the magnetic field of the permanent magnet and the armature magnetic field of the primary winding respectively, and their magnetic field analysis model is established in Fig. 4 and Fig.5.

**FIGURE 4.** Permanent magnet magnetic field analysis model.

**FIGURE 5.** Primary winding magnetic field analysis model.

Using the equivalent magnetizing current theory to consider the permanent magnet as the current-carrying coil, whose current density can get by

\[
J_p(x) = -\frac{4B_t}{\pi \mu_0} \sum_{n=1}^{\infty} \sin \left(\frac{(2n-1)\pi b_m}{2\tau}\right) \sin \left(\frac{(2n-1)\pi x}{\tau}\right)
\]

(2)

The equations of magnetic vector potential \( A_p \) establishes according to Maxwell’s equations as

\[
\begin{align*}
\frac{\partial^2 A_{p1}}{\partial x^2} + \frac{\partial^2 A_{p1}}{\partial y^2} &= -\mu_0 J_p \quad 0 < y < h_m \\
\frac{\partial^2 A_{p2}}{\partial x^2} + \frac{\partial^2 A_{p2}}{\partial y^2} &= 0 \quad h_m < y < H \\
\end{align*}
\]

(3)

The general solution obtained by the method of separating variables is

\[
A_{p1} = (C_1 \text{ch} n y + D_1 \text{sh} n y) \left( E_1 \cos k_n x + F_1 \sin k_n x \right) \\
- \ldots - \frac{4B_t}{\pi \mu_0} \sum_{n=1}^{\infty} \frac{1}{\left(\frac{(2n-1)\pi b_m}{2\tau}\right)^2} \sin \left(\frac{(2n-1)\pi x}{\tau}\right) \\
\times \frac{\sin \left(\frac{(2n-1)\pi x}{\tau}\right)}{\tau}
\]

\[
A_{p2} = (C_2 \text{ch} n x + D_2 \text{sh} n x) \left( E_2 \cos k_n x + F_2 \sin k_n x \right)
\]

(4)

Equation (5) can be obtained according to the boundary conditions as

\[
\begin{align*}
C_1 &= C_1 F_1 = F_n \frac{\text{ch} n (H - h_m)}{\text{sh} n H} \\
D_1 &= 0 \\
E_1 &= 0 \\
C_2 &= C_2 F_2 = -F_n \frac{\text{ch} n H}{\text{sh} n H} \text{sh} n h_m \\
D_2 &= F_n \text{sh} n h_m \\
E_2 &= 0 \\
\end{align*}
\]

(5)

Among them, the variable \( k_n, F_n \) can be expressed as

\[
\begin{align*}
k_n &= \frac{(2n-1)\pi}{\tau} \\
F_n &= \frac{4B_t}{\pi \mu_0} \sum_{n=1}^{\infty} \frac{1}{\left(\frac{(2n-1)\pi b_m}{2\tau}\right)^2} \sin \left(\frac{(2n-1)\pi x}{\tau}\right) \\
\end{align*}
\]

(6)

Therefore, the vector magnetomotive potential \( A_{p1}, A_{p2} \) and magnetic field density \( B_{p1}, B_{p2} \) in the permanent magnet area and the air-gap field area respectively are expressed as

\[
\begin{align*}
A_{p1} &= F_n \frac{\text{sh} n (H - h_m)}{\text{sh} n H} \sin k_n x \text{ch} n y - F_n \sin k_n x \\
B_{p1x} &= F_n \frac{\text{sh} n (H - h_m)}{\text{sh} n H} \sin k_n x \text{sh} n y \\
B_{p1y} &= -F_n k_n \frac{\text{sh} n H}{\text{sh} n H} \cos k_n x \text{ch} n y \\
&+ F_n k_n \cos k_n x \\
\end{align*}
\]

(7)

\[
\begin{align*}
A_{p2} &= -F_n \frac{\text{sh} n h_m}{\text{sh} n H} \sin k_n x \text{ch} n (H - y) \\
B_{p2x} &= F_n \frac{\text{sh} n h_m}{\text{sh} n H} \sin k_n x \text{sh} n (H - y) \\
B_{p2y} &= F_n k_n \frac{\text{sh} n h_m}{\text{sh} n H} \cos k_n x \text{ch} n (H - y) \\
\end{align*}
\]

(8)

According to the above method, the magnetic field excited by the primary windings is analyzed based on the equivalent current sheet theory, the current density \( J_s(x) \) is

\[
J_s(x) = \frac{2}{\pi} \sum_{n=1}^{\infty} \frac{1}{n} \left( \cos \left[ \frac{n \pi (3 + k)}{6} \right] - \cos \left[ \frac{n \pi (3 - k)}{6} \right] \right) \\
\cdot \ldots \cdot \left[ J_a \sin \left( \frac{n \pi}{3} (x + t) \right) + J_b \sin \left( \frac{n \pi}{3} (x - t) \right) \\
- J_c \sin \left( \frac{n \pi}{3} t \right) \right]
\]

(9)
The magnetic field equation for the vector magnetic potential of the primary windings is established by Maxwell’s equations according to Fig. 5 as

\[
\begin{cases}
\frac{\partial^2 A_{11}}{\partial x^2} + \frac{\partial^2 A_{11}}{\partial y^2} = 0 & 0 < y < H \\
\frac{\partial^2 A_{21}}{\partial x^2} + \frac{\partial^2 A_{21}}{\partial y^2} = -\mu_0 J_s & H < y < H_1
\end{cases}
\]  

(10)

Using the method of separating variables to (10), the general solution can be obtained as

\[
A_{11} = (c_1 \text{chp}_{ny} + d_1 \text{shp}_{ny})(c_1 \cos p_n x + f_1 \sin p_n x) + \ldots \\
A_{21} = (c_2 \text{chp}_{ny} + d_2 \text{shp}_{ny})(c_2 \cos p_n x + f_2 \sin p_n x) + \ldots \\
+ \frac{18\pi^2 \mu_0}{\pi^3} \sum_{n=1}^{\infty} \frac{1}{n^3} \cos \left(\frac{n\pi (3 + k)}{6}\right) \\
- \cos \left(\frac{n\pi (3 - k)}{6}\right) \\
+ J_b \sin \left[\frac{n\pi}{3f} (x - t)\right] - J_c \sin \left[\frac{n\pi t}{3f}\right]
\]

(11)

According to the boundary conditions, the correlation coefficient expression can be obtained as

\[
\begin{cases}
c_1 = c_1 f_1 = G_n \frac{\text{shp}_{n} (H_1 - H)}{\text{shp}_{n} H_1} e^{(p_n H)^2} \\
d_1 = 0 \\
e_1 = 0 \\
c_2 = c_2 f_2 = -G_n \frac{\text{chp}_{n} H_1 \text{shp}_{n} H}{\text{shp}_{n} H_1} e^{(p_n H)^2} \\
d_2 = G_n \text{shp}_{n} H e^{(p_n H)^2} \\
e_2 = 0
\end{cases}
\]

(12)

Among them, the variable \( p_n, G_n \) can be got by

\[
G_n = \frac{18\pi^2 \mu_0}{\pi^3} \sum_{n=1}^{\infty} \frac{1}{n^3} \cos \left(\frac{n\pi (3 + k)}{6}\right) \\
- \cos \left(\frac{n\pi (3 - k)}{6}\right)
\]

(13)

Therefore, the equations for the vector magnetic potential \( A_{11}, A_{21} \) and magnetic field density \( B_{11}, B_{21} \) in the air-gap field area and the primary winding area are

\[
A_{11} = G_n \frac{\text{shp}_{n} (H_1 - H)}{\text{shp}_{n} H_1} e^{(p_n H)^2} \text{chp}_{n} y \cdot \ldots \\
\cdot \left[ J_a \sin [p_n (x + t)] + J_b \sin [p_n (x - t)] - J_c \sin [p_n x] \right]
\]

\[
B_{11x} = G_n \frac{\text{shp}_{n} (H_1 - H)}{\text{shp}_{n} H_1} e^{(p_n H)^2} \text{shp}_{n} y \cdot \ldots \\
\cdot \left[ J_a \sin [p_n (x + t)] + J_b \sin [p_n (x - t)] - J_c \sin [p_n x] \right]
\]

\[
B_{11y} = -G_n \frac{\text{shp}_{n} (H_1 - H)}{\text{shp}_{n} H_1} e^{(p_n H)^2} \text{chp}_{n} y \cdot \ldots \\
\cdot \left[ J_a \cos [p_n (x + t)] + J_b \cos [p_n (x - t)] - J_c \cos [p_n x] \right]
\]

(14)

\[
\begin{align*}
A_{12} &= -G_n \left( \frac{\text{shp}_{n} H e^{(p_n H)^2}}{\text{shp}_{n} H_1} \right) \text{chp}_{n} (H_1 - y) - 1) \cdot \ldots \\
&\cdot \left[ J_a \sin [p_n (x + t)] + J_b \sin [p_n (x - t)] - J_c \sin [p_n x] \right] \\
B_{12x} &= G_n \frac{\text{shp}_{n} H e^{(p_n H)^2}}{\text{shp}_{n} H_1} \text{chp}_{n} (H_1 - y) - 1) \cdot \ldots \\
&\cdot \left[ J_a \sin [p_n (x + t)] + J_b \sin [p_n (x - t)] - J_c \sin [p_n x] \right]
\end{align*}
\]

(15)

The magnetic field density \( B_{11}, B_{12} \) generated by the primary winding and the permanent magnet in the air-gap region respectively can be superimposed to get the equation of the air-gap magnetic field density \( B_{air} \)

\[
\begin{align*}
B_{air,x} &= B_{p2x} + B_{s1x} = F_n k_n \frac{\text{shk}_{n} h_{n}}{\text{shk}_{n} H} \text{sin} k_n \text{xshk}_{n} (H - y) - \ldots \\
&+ G_n \frac{\text{shp}_{n} (H_1 - H)}{\text{shp}_{n} H_1} e^{(p_n H)^2} \text{chp}_{n} \cdot \ldots \\
&\cdot \left[ J_a \sin [p_n (x + t)] + J_b \sin [p_n (x - t)] - J_c \sin [p_n x] \right]
\end{align*}
\]

(16)

\[
\begin{align*}
B_{air,y} &= B_{p2y} + B_{s1y} = F_n k_n \frac{\text{shk}_{n} h_{n}}{\text{shk}_{n} H} \text{cos} k_n \text{xshk}_{n} (H - y) - \ldots \\
&- G_n \frac{\text{shp}_{n} (H_1 - H)}{\text{shp}_{n} H_1} e^{(p_n H)^2} \text{chp}_{n} \cdot \ldots \\
&\cdot \left[ J_a \cos [p_n (x + t)] + J_b \cos [p_n (x - t)] - J_c \cos [p_n x] \right]
\end{align*}
\]

(17)

\[
\begin{align*}
C. \ \text{ELECTROMAGNETIC THRUST CALCULATION}
\end{align*}
\]

The electromagnetic force of PMLSM is mainly composed of horizontal thrust and normal suction, and the effective thrust is mainly horizontal thrust. According to the Maxwell tensor method, the expression of electromagnetic thrust can be obtained along the integral path shown in Fig. 6 as

\[
F_x = \int_{A_1D_1} \left( B_x^2 - B_y^2 \right) dy - \int_{C_1B_1} \left( B_y^2 - B_x^2 \right) dy + \ldots \\
+ \int_{A_2D_2} \left( B_x^2 - B_y^2 \right) dy - \int_{C_2B_2} \left( B_y^2 - B_x^2 \right) dy + \ldots \\
+ \int_{B_3C} \left( B_x^2 - B_y^2 \right) dy - \int_{D_3A} \left( B_y^2 - B_x^2 \right) dy
\]

(14)
FIGURE 6. Electromagnetic force integration path of PMLSM.

\[
+ \ldots + \frac{W}{\mu_0} \left[ \int_{A_1A_2} B_x B_y dx + \int_{D_1C_1} B_x B_y dx \right.

+ \int_{B_1A_2} B_x B_y dx + \ldots + \int_{B_nB_n} B_x B_y dx - \int_{C_1D_1} B_x B_y dx \right]

\]

(17)

Among them, \(B_x\) and \(B_y\) are the magnetic field density components of the air-gap field along the x-axis and the y-axis.

Since the core permeability is infinite, so

\[
\int B_x B_y dx = 0
\]

(18)

Therefore, (17) can be simplified as

\[
F_x = \frac{W}{2\mu_0} \left[ \int_{A_1D_1} \left( B_x^2 - B_y^2 \right) dy - \int_{A_1D_1} \left( B_x^2 - B_y^2 \right) dy + \ldots 

+ \int_{A_1D_1} \left( B_x^2 - B_y^2 \right) dy - \int_{A_1D_1} \left( B_x^2 - B_y^2 \right) dy + \ldots 

+ \int_{B_nB_n} \left( B_x^2 - B_y^2 \right) dy - \int_{B_nB_n} \left( B_x^2 - B_y^2 \right) dy \right]

\]

(19)

IV. PERFORMANCE ANALYSIS

The motor parameters designed in this paper are shown in Table 1. The motor frequency is 502Hz, the effective value of the output current is 18A, and the synchronous speed is 87.7m/s. The electromagnetic field of the motor is simulated by ANSYS software.

A. PERFORMANCE ANALYSIS OF PMLSM

Fig.7 is a diagram of the PMLSM flux density. Because of the ring windings, the upper and lower permanent magnets have opposite polarities, so the flux density passes through the primary core yoke, resulting in saturation of the core yoke to some degree.

Fig.8 indicates the air-gap field curve at no-load condition, which has the feature of a flat-topped wave, the amplitude of the air-gap density fundamental wave is about 0.813T, which accounts for about 74% of the air-gap flux density amplitude, the 3rd, 5th, and 7th harmonic content is relatively large. The theoretical value is consistent with the calculation result of the finite element method.

Fig.9 displays the electromagnetic thrust and detent force of the PMLSM, the average thrust calculated by the analytical calculation and the finite element is 152N and 157N respectively, which are approximately equal. However, the peak-to-peak thrust fluctuation is about 22N, which is about 14% of the average value.

B. PERFORMANCE COMPARISON OF TOROIDAL AND LINEAR STRUCTURES PMLSM

Due to the long stroke required to accelerate the secondary and the high manufacturing cost of the linear structure, the toroidal structure is proposed to replace the linear structure, so the performance of the toroidal structure should be consistent with the linear structure.

Fig. 10 shows the flux density diagram of the toroidal structure motor. Since flux density passes through the primary core yoke, the core yoke also has saturation to some degree.

TABLE 1. Electromagnetic parameters of prototype.

| Symbol | Quantity                  | Value   |
|--------|---------------------------|---------|
| \(r\)  | pole pitch                | 0.084m  |
| \(h_x\) | permanent magnet width    | 13.3mm  |
| \(b_x\) | permanent magnet length   | 61mm    |
| \(\delta\) | air gap length            | 5mm     |
| \(N\)  | number of conductors per slot | 16         |
| \(a\)  | parallel root number      | 4       |
| \(h_0\) | primary groove depth      | 13.3mm  |
| \(h_1\) | primary yoke thickness    | 23.4mm  |
| \(b_1\) | back iron thickness       | 20mm    |
| \(b_0\) | primary groove width      | 6mm     |
| \(Q\)  | total number of slots     | 216     |
| \(p\)  | number of slots per phase | 2       |
| \(l\)  | primary width             | 30mm    |

FIGURE 7. Magnetic flux density graph of PMLSM.
Fig. 11 is the air-gap flux density curve at no load, which also has the feature of a flat-topped wave. The amplitude of the air-gap density fundamental wave is about 0.7T, which accounts for about 63% of the air-gap flux density amplitude, the 3rd, 5th and 7th harmonic content is larger than linear structure.

Fig. 12 indicates the electromagnetic force and detent force of the TPMLSM, the average thrust of the TPMLSM and the PMLSM is 153.4N and 157N respectively, which are approximately equal, the peak-to-peak thrust fluctuation is about 23N, which is about 15% of the average value.

C. STRUCTURE OPTIMIZATION

From the above analysis, the thrust fluctuates greatly, accordingly, the motor control is more difficult. The edge force and the cogging force caused by the end effect and the slotting effect respectively are the main reason for the thrust ripple of PMLSM [13], [14]. From the design perspective, the thrust ripple reduction methods of PMLSM mainly include optimizing the length of the primary core [15], changing the width of the permanent magnet and the length of air-gap [16]. Among them, optimizing the length of the core can weaken the influence of the edge force and changing the width of permanent magnet can weaken the cogging force. This paper improves the above problems by adjusting the permanent...
magnet, air gap and core size, these parameters are scanned parametrically in the finite element software and then the motor parameters with small thrust ripples are obtained. The adjusted parameters are presented in Table 2.

Fig. 13 is the no-load air-gap flux density curve of the optimized structure. From Fig. 13 we can see that the air-gap field waveform is closer to sinusoidal when there is no load. The amplitude of fundamental wave is about 0.88T, which accounts for about 63% of the air gap magnetic density amplitude. The fundamental wave amplitude has increased.

Fig. 14 shows the electromagnetic thrust and magnetic resistance of the toroidal structure motor, the average thrust of the annular structure is 151.6N, and the peak-to-peak thrust fluctuation is about 8.8N, about 5.8% of the average, which is smaller than the linear structure and the toroidal structure before optimization.

V. CONCLUSION
This paper proposes a toroidal long primary PMLSM for periodic transient conditions, the air-gap density and electromagnetic thrust of the linear and toroidal structure are analyzed, then the toroidal structure is optimized and analyzed by FEM. The results show that:

1) The acceleration and braking distance of the toroidal structure within the specified final speed range is not limited by the stroke compared to linear structure under the same thrust performance index, which saves space and reduces costs.

2) The thrust required for the toroidal structure to reach the specified final speed is much smaller than that of the linear structure under the same volume requirements, so the power level is greatly reduced.

3) The thrust ripple of TPMLSM is reduced from 15% to 5.8% by optimizing the length of the air-gap and the width of the permanent magnet.

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TABLE 2. Electromagnetic parameters of optimized prototype.

| Symbol | Quantity | Value |
|--------|----------|-------|
| r      | pole pitch | 0.084m |
| h_p    | permanent magnet width | 15mm |
| b_p    | permanent magnet length | 48mm |
| δ      | air gap length | 4mm |
| N      | number of conductors per slot | 16 |
| a      | parallel root number | 4 |
| h_0    | primary groove depth | 13.3mm |
| h_1    | primary yoke thickness | 25.4mm |
| h_2    | back iron thickness | 20mm |
| b_0    | primary groove width | 6mm |
| Q      | total number of slots | 216 |
| p      | number of slots per pole per phase | 2 |
| l      | primary width | 30mm |

FIGURE 13. No load air-gap magnetic field curve of optimized structure.

FIGURE 14. Electromagnetic thrust and detent force of optimized structure.
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