Design Optimization of Improved Halbach Tubular Permanent Magnet Linear Synchronous Motor with Less Permanent Magnet

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Abstract. To reduce the permanent magnet (PM) usage and cost, the improved Halbach tubular permanent magnet linear synchronous motor (IH-TPMLSM), which has unequal thickness of the radial and axial magnetized PMs located in the mover, is developed in this paper. Taking the maximum average thrust as the optimization objective, the single-step optimization method based on sensitivity analysis is used to optimize motor under the same current density by finite element (FE) analysis. The influence of the pole-pitch τ on the detent force is analyzed. According to the comparison of optimized TPMLSMs, the results show that when pole-pitch τ = 30.5mm and the full-pitched winding disposition τs = 31.5mm, the detent force is reduced by 55.87%. Finally, the open-circuit back EMF, air gap flux density, the thrust of the IH-TPMLSM and the quasi Halbach TPMLSM (QH-TPMLSM) are compared. The quantity of PMs of the IH-TPMLSM is 15.27% lower and the average thrust is 4.01% higher than that of QH-TPMLSM. Meanwhile the thrust ripple is reduced by 36.12%.

1. Introduction

As a kind of linear motor, tubular permanent magnet linear synchronous motor (TPMLSM) develops rapidly because of its less winding ends and no lateral edge effect. The magnetization PMs of TPMLSM can be divided into axial magnetization PMs [1], radial magnetization PMs [2], and Halbach magnetization PMs [3]. It can be seen from reference [4] that compared with axial or radial magnetization PM motors, using quasi Halbach magnetization PMs can improve the sinusoidal of air gap flux density, increase the air gap flux density and increase the thrust of motor. However, the quantity of PMs usage in the quasi Halbach magnetization PMs is large. In the case of high thrust requirements, such as deep well pumping systems and mining systems, TPMLSM is long along the axial direction. This makes it very expensive to make a TPMLSM. So it is more important to reduce the PM usage and cost. Without reducing the average thrust of TPMLSM, it is significant to reduce the quantity of PMs.

In this paper, an improved Halbach tubular permanent magnet linear synchronous motor (IH-TPMLSM) with less PMs is proposed. The radial thickness of the radial magnetization PMs is reduced...
and installed near the air gap. The back iron is installed on the side away from the air gap. This structure shows the advantages of the quasi Halbach PMs at the air gap. The finite element (FE) simulation model is established and the optimization sequence of motor parameters is determined by sensitivity analysis. The optimization is carried out with the maximum average thrust as the objective. In view of the large detent force of IH-TPMLSM, changing the pole-pitch reduces the detent force and the thrust ripple. Finally, the performances of IH-TPMLSM and QH-TPMLSM are compared.

2. Structure and principle of motor

Figure 1. (a) is the cross section diagram of IH-TPMLSM and Figure 1.(b) is the cross section diagram of QH-TPMLSM. The thickness of radial magnetization PMs is reduced in Figure 1. (a), which can reduce the quantity of PMs while maintaining the large average thrust. The direction of arrow in the shadow part is the magnetization direction of PMs. Different from the rotating motor, the armature winding of linear motor produces traveling wave magnetic field along the axial direction. The traveling wave magnetic field is equivalent to the rotating magnetic field of the rotating motor. The interaction between the excitation magnetic field produced by the PMs and the traveling wave magnetic field make the mover subject to thrust.

![Cross section of two motors](image)

**Figure 1. Cross section of two motors. (a) IH-TPMLSM, (b) QH-TPMLSM**

Figure 2 shows the design parameters of IH-TPMLSM. It is known that the thrust of TPMLSM is proportional to air gap flux density, armature winding current and motor volume. Due to the requirements of the working environment, the actual motor can not be infinite. Especially the outer diameter of the motor will be limited. Due to the problems of motor heating and magnetic saturation, the outer radius of the motor is fixed. The split ratio is suggested to be 0.5-0.6[5]. The ratio of axial length of radial magnetization PMs to pole-pitch is $\beta$. When $\beta = 0.8$, the high order harmonic minimum of air gap flux density, and the thrust ripple is small [6]. Therefore, the initial setting of $r_{mr}$ is 25.2mm. The increase in the quantity of PMs leads to an intensified armature reaction. The size of the PMs is too small, which will cause processing difficulties and increase the risk of permanent magnet
demagnetization. Therefore, the initial length of the radial length of radial magnetization PMs is 4.5 mm, and the radial length of axial magnetization PMs is 12 mm. Initial design parameters of IH-TPMLSM are shown in Table 1.

![Design parameters of IH-TPMLSM](image)

**Figure 2.** Design parameters of IH-TPMLSM

| Parameters                                | Initial value | Parameters                                | Initial value |
|-------------------------------------------|---------------|-------------------------------------------|---------------|
| pole-pitch, \( \tau \)                   | 31.5 mm       | Current density, \( J \)                  | 10 A/mm²      |
| air gap, \( g \)                          | 3 mm          | Stator back iron thickness, \( h_t \)     | 3.5 mm        |
| axial length of radial magnetization PMs, \( \tau_{mr} \) | 25.2 mm       | radial length of radial magnetization PMs, \( P_r \) | 4.5 mm        |
| Spilt ratio, \( \lambda \)               | 0.58          | Quantity of PMs, \( V_{pm} \)            | 24.71 cm³     |
| Stator tooth width, \( b_t \)            | 2.5 mm        | Average thrust, \( F_{avg} \)            | 691.76 N      |

The current density is calculated as follows:

\[
J = \frac{N_a I}{K_p S}
\]  

(1)

Where \( J \) is the current density of IH-TPMLM, \( N_a \) is the number of turns of each winding, \( I \) is the current of armature winding, \( K_p \) is the slot packing factor, \( S \) is the slot area.

3. **Design and optimization**

3.1. **Sensitivity analysis and optimization**

In the process of motor optimization, there is more than one optimization design parameter. Through sensitivity analysis, the optimization of different design parameters can be set in priority order. According to this order, the optimization of motor can better solve the optimization problem of multi design parameter motor, and can be obtained better optimization results[7]. In sensitivity analysis, \( x_i \) is the design parameter variable and \( F(x) \) is the objective function. The objective functions are power, thrust and so on [8]. Therefore, the sensitivity of the \( i \)th parameter variable value at \( x_0 \) can be expressed as:

\[
S_i = \frac{\partial F(x)}{\partial x_i} \bigg|_{x=x_0}
\]

(2)
Taking the average thrust of the motor as the optimization objective, the first derivative of the average thrust to the design parameter is $S_i$. The value of $S_i$ indicates the sensitivity of the average thrust to the design parameter. The larger $S_i$, the more sensitive the average thrust is to the design parameter.

Table 2. Scope of sensitivity analysis

| Parameters | Scope | Unit |
|------------|-------|------|
| axial length of radial magnetization PMs, $\tau_{mr}$ | 20.2~30.2 | mm |
| radial length of radial magnetization PMs, $P_r$ | 3~8 | mm |
| Stator tooth width, $b_t$ | 1.5~3.5 | mm |
| Stator back iron thickness, $h_t$ | 1~4 | mm |
| Spilt ratio, $\lambda$ | 0.48~0.68 | - |

From Figure 3.(a) it shows that the sensitivity from high to low is $\lambda$, $\tau_{mr}$, $P_r$, $h_t$ and $b_t$ respectively. The design parameters are simulated by finite element parameterization in sequence, and the
optimization results are shown in (b)-(f). It can be seen from (b), (c) and (d) that with the change of design parameters, the quantity of PMs also changes. The quantity of PMs increases after the optimization of $\lambda$, $\tau_{mr}$ and $P_r$. It can be seen from (e) and (f) that $h_t$ and $b_t$ will not affect the quantity of PMs. With the increase of each parameter, the average thrust is not monotonic, thus the parameter value of the maximum average thrust can be selected. The result is $\lambda$=0.53, $\tau_{mr}$=17mm, $P_r$=8mm, $h_t$=2.5mm, $b_t$=2.5mm, $V_{pm}$=36.826 cm$^3$, $F_{avg}$=888.5N. The average thrust of the optimized motor is increased by 28.45%.

3.2. Change pole-pitch
IH-TPMLM has great detent force. When $\tau \neq \tau_s$, the harmonics and braking force of the open circuit back EMF are reduced. Through the finite element simulation analysis, when $\tau = 30.5$mm, $\tau_s = 31.5$mm, the detent force is the smallest.

![Figure 4. Result of simulation. (a) open-circuit back EMF (speed=0.63m/s). (b) harmonic of open-circuit back EMF. (c) Detent force](image)

Figure 4. Result of simulation. (a) open-circuit back EMF (speed=0.63m/s). (b) harmonic of open-circuit back EMF. (c) Detent force

Figure 4.(a) shows that the waveform of open-current back EMF of the two motors is similar, and the maximum value of open-current back EMF is larger when $\tau = 31.5$mm. Figure 4. (b) shows that when $\tau = 30.5$mm, the fundamental wave of open-current back EMF is larger and the 3rd, 5th and 7th harmonics are reduced. Figure 4. (c) shows that the detent force of the motor is reduced by about 55.87%. In this process, the change of the quantity of PMs is ignored.

4. Motor comparison
QH-TPMLM is optimized under the same current density. The parameter sizes of the two motors are shown in Table 3.
Table 3. Size parameters of two kinds of motors

| Parameters | Value | Value |
|------------|-------|-------|
| IH-TPMLSM  | QH-TPMLSM |
| $\tau$    | 30.5mm | 31.5mm |
| $\tau_{mr}$ | 17mm | 17mm |
| $P_r$     | 8mm | 12mm |
| $b_t$     | 2.5mm | 2.5mm |
| $h_t$     | 2.5mm | 2.6mm |
| $\lambda$ | 0.53 | 0.525 |
| $S$       | $175.52mm^2$ | $175.38mm^2$ |
| $V_{pm}$  | 36.826cm$^3$ | 43.463cm$^3$ |
| $F_{avg}$ | 914.2N | 879.1N |

It can be seen from table 3 that $\tau_{mr}$ and $b_t$ of the two motors are equal. The $\lambda$ of QH-TPMLSM is smaller, and the $h_t$ of QH-TPMLSM is larger. This is caused by magnetic saturation. As envisaged, the $P_r$ of IH-TPMLSM is smaller. The average thrust of IH-TPMLSM is 4.01% higher than that of QH-TPMLSM, and the quantity of PMs is 15.27% lower. As for Figure 5, the fundamental wave of open-circuit back EMF of IH-TPMLSM is higher than that of QH-TPMLSM, and the higher harmonic of IH-TPMLSM is lower than that of QH-TPMLSM. The thrust ripple of IH-TPMLSM is reduced by 36.12% due to the reduction of higher harmonic of IH-TPMLSM.

Figure 5. Result of simulation (speed=0.63m/s). (a) open-circuit back EMF. (b) harmonic of open-circuit back EMF. (c) Detent force.

5. Conclusion
This paper presents the IH-TPMLSM with less permanent magnet. The finite element simulation model was established, and the motor parameter are optimized by single step optimization based on sensitivity analysis. When $\tau \neq \tau_s$, the detent force of the motor is effectively suppressed. According to
the comparison of optimized TPMLSMs, it shows that compared with QH-TPMLSM, the average thrust of IH-TPMLSM increases by 4.01%, and the quantity of PMs about IH-TPMLSM decreases by 15.27%. Therefore, the cost of IH-TPMLSM is lower. When the current density is 10A/mm², the thrust ripple of IH-TPMLSM is reduced by 36.12%. IH-TPMLSM has more advantages when it is required by long stroke and high average thrust.

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