Modeling Analysis and Parameters Calculation of Permanent Magnet Linear Synchronous Motor

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Abstract—**Permanent magnet linear synchronous motor (PMLSM) has several advantages, such as simple structure, small volume, high force, and so on. It is a research focus and difficulties in the research field of motor. Because PMLSM is different from the traditional rotary motors in structure and running state, it is difficult for to build its precise mathematical model by analytical method. The asymmetry of the three-phase winding electromagnetic and electrical parameters of open PMLSM in a low-speed working zone is impossible to take into account. In this paper, the difference between the permanent magnet linear synchronous motor and traditional motors are analyzed. And then, a non-linear, asymmetric and variable parameter space state model is built, considering the structural and running characteristics of PMLSM. The proposed model needs all kinds of parameters of PMLSM, including self-inductance, mutual inductance, flux linkage, etc. So, a finite element calculation and actual measurement of the required parameters of a prototype PMLSM are done, respectively. The influence of air-gap on the inductance parameters was analyzed.**

Index Terms—**permanent magnet linear synchronous motor (PMLSM), space state, modeling, inductance, parameters calculation**

I. INTRODUCTION

Linear motor with the advantages of simple structure, low noise, high precision, easy maintenance etc., directly implements linear motion without gears, chains, connecting rod and other intermediate conversion. So, linear motor has been widely used in transportation, industrial equipment, logistics, military, modern high-precision machine tools and other fields, gradually into people's daily life [1~5].

Permanent magnet linear synchronous motor (PMLSM) combining the advantages of permanent magnet motor and linear motor. PMLSM is greatly different from the traditional motors both in structure and in the running state. The yoke of PMLSM is open, trough of its end is half-filled and winding is discontinuous, which cause the asymmetry of electromagnetic parameters. If the traditional phase equivalent circuit is still adopted, it will bring large errors. PMLSM with the rectangular teeth and slots, the air gap is large, and the motor magnetic flux leakage increases. Therefore, it is difficult to adopt traditional analytical method. Although the magnetic resistance alveolar component of PMLSM equals to that of the traditional permanent magnet synchronous rotary motor, and the end component is much larger than the alveolar component. When running in low-frequency, all the prototype PMLSMs at home and abroad have the characteristics of large resistance and small reactance, so the power angle characteristic equation of traditional synchronous motor is no longer applicable. In power supply of voltage inverter, the voltage is non-sinusoidal, and the motor running state is complex [6~9].

The voltage, current, and flux of PMLSM are non-sinusoid, so it is difficult to use the analytical method to establish the precise mathematical model. At present, there are two PMLSM dynamic models widely used at home and abroad: one is the d-q model based on moving coordinate system; the other is the direct field-circuit model. The former assumed that the excitation magnetic field and armature reaction magnetic field are distributed by sine law, which is unable to take the special structural and running characteristics of PMLSM. Therefore, it is clearly insufficient. The latter one had a dynamic characteristics simulation of the inverter-fed PMLSM using time-stepping finite element method and moving grid technique, which not only involves harmonic components of the magnetic field, but also takes into account the impact of asymmetric and nonlinear, so it has a higher accuracy [10~12]. When the model is larger and complex, modeling and calculation are time-consuming.

In this paper, the difference between the permanent magnet linear synchronous motor and traditional motors are analyzed. Then, from the reality of PMLSM, a space state model of PMLSM is built, and a finite element calculation and actual measurement of the required self-inductance, mutual inductance of the space state model with a prototype PMLSM are done, respectively.

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II. SPACE STATE MODELING OF PMLSM

A. External Circuit Equation

When primary is completely in the range of the secondary, the absolute values of self-inductance and mutual inductance and the amplitude value of the excitation flux are unchanged [13~15].

Armature windings adopt the method of star without neutral line connection, as is shown in Figure. 1.

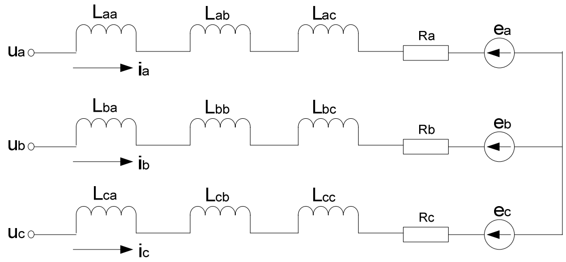

Figure 1. Equalization circuit of PMLSM.

Because of the lateral end of the PMLSM, the primary winding is discrete, which results in the asymmetric of the electromagnetic parameters. And the current of the midpoint potential of the star must not be zero at low speed. As Figure 1 shown, the voltage balance equation of the three-phase windings of is:

$$\begin{cases} e_a + Ri_a + L_\sigma \dfrac{di_a}{dt} = u_a - u_n \\ e_b + Ri_b + L_\sigma \dfrac{di_b}{dt} = u_b - u_n \\ e_c + Ri_c + L_\sigma \dfrac{di_c}{dt} = u_c - u_n \end{cases} \tag{1}$$

where, e_a, e_b, e_c are the EMF of three-phase winding; ia, ib, ic are the current of three-phase winding; u_n is the star point potential; R is the winding resistance; L_σ is the end leakage inductance of the three-phase winding.

Line voltage and phase voltage equations are:

$$\begin{cases} u_{ac} = u_{an'} - u_{cn'} \\ u_{ab} = u_{an'} - u_{bn'} \\ u_{cb} = u_{cn'} - u_{bn'} \end{cases} \tag{2}$$

$$\begin{cases} u_{an} = u_{an'} - u_{nn'} \\ u_{bn} = u_{bn'} - u_{nn'} \\ u_{cn} = u_{cn'} - u_{nn'} \end{cases} \tag{3}$$

So, the voltage between the three-phase winding star point and the midpoint of the inverter is:

$$u_{nn'} = \frac{1}{3}(u_{an'} + u_{bn'} + u_{cn'}) - \frac{1}{3}(u_{an} + u_{bn} + u_{cn}) \tag{4}$$

The relationship of three-phase current is:

$$i_a + i_b + i_c = 0 \tag{5}$$

B. Space State Model

As Figure 1 shown, the voltage equation of PMLSM is:

$$\begin{cases} u_a = r_a i_a + p\psi_a \\ u_b = r_b i_b + p\psi_b \\ u_c = r_c i_c + p\psi_c \end{cases} \tag{6}$$

Flux equation of PMLSM is:

$$\begin{cases} \psi_a = L_{aa} i_a + L_{ab} i_b + L_{ac} i_c + \psi_{am} \\ \psi_b = L_{ba} i_a + L_{bb} i_b + L_{bc} i_c + \psi_{bm} \\ \psi_c = L_{ca} i_a + L_{cb} i_b + L_{cc} i_c + \psi_{cm} \end{cases} \tag{7}$$

Put (1) into (2), it will be transformed into (3):

$$\begin{aligned} \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} &= \begin{bmatrix} r_a & 0 & 0 \\ 0 & r_b & 0 \\ 0 & 0 & r_c \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + p \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \\ &+ \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} p \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + p \begin{bmatrix} \psi_{am} \\ \psi_{bm} \\ \psi_{cm} \end{bmatrix} \end{aligned} \tag{8}$$

Assume that the self-inductance and mutual inductance of phase winding is a function of displacement, the following will be obtained:

$$\begin{aligned} \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} &= \begin{bmatrix} r_a & 0 & 0 \\ 0 & r_b & 0 \\ 0 & 0 & r_c \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \\ &+ v \begin{bmatrix} p_x L_{aa} & p_x L_{ab} & p_x L_{ac} \\ p_x L_{ba} & p_x L_{bb} & p_x L_{bc} \\ p_x L_{ca} & p_x L_{cb} & p_x L_{cc} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \\ &+ \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} \begin{bmatrix} pi_a \\ pi_b \\ pi_c \end{bmatrix} + \begin{bmatrix} p\psi_{am} \\ p\psi_{bm} \\ p\psi_{cm} \end{bmatrix} \\ &= \begin{bmatrix} r_a + vp_x L_{aa} & vp_x L_{ab} & vp_x L_{ac} \\ vp_x L_{ba} & r_b + vp_x L_{bb} & vp_x L_{bc} \\ vp_x L_{ca} & vp_x L_{cb} & r_c + vp_x L_{cc} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \\ &+ \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} \begin{bmatrix} pi_a \\ pi_b \\ pi_c \end{bmatrix} + \begin{bmatrix} p\psi_{am} \\ p\psi_{bm} \\ p\psi_{cm} \end{bmatrix} \end{aligned} \tag{9}$$

After transpose, the results will be:

$$\begin{aligned} \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} \begin{bmatrix} pi_a \\ pi_b \\ pi_c \end{bmatrix} &= \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} - \begin{bmatrix} p\psi_{am} \\ p\psi_{bm} \\ p\psi_{cm} \end{bmatrix} \\ &- \begin{bmatrix} r_a + vp_x L_{aa} & vp_x L_{ab} & vp_x L_{ac} \\ vp_x L_{ba} & r_b + vp_x L_{bb} & vp_x L_{bc} \\ vp_x L_{ca} & vp_x L_{cb} & r_c + vp_x L_{cc} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \end{aligned} \tag{10}$$

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$$\begin{bmatrix} pi_a \\ pi_b \\ pi_c \end{bmatrix} = \begin{bmatrix} & & \\ & L & \\ & & \end{bmatrix}^{-1} \left\{ \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} - \begin{bmatrix} p\psi_{am} \\ p\psi_{bm} \\ p\psi_{cm} \end{bmatrix} - \begin{bmatrix} r_a + vp_xL_{aa} & vp_xL_{ab} & vp_xL_{ac} \\ vp_xL_{ba} & r_b + vp_xL_{bb} & vp_xL_{bc} \\ vp_xL_{ca} & vp_xL_{cb} & r_c + vp_xL_{cc} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \right\} \tag{11}$$

where

$$\begin{bmatrix} & & \\ & L & \\ & & \end{bmatrix}^{-1} = \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix}^{-1}$$

When the self-inductance and mutual inductance is not a function of displacement, the above equation can be simplified to the following formula:

$$\begin{bmatrix} pi_a \\ pi_b \\ pi_c \end{bmatrix} = \begin{bmatrix} & & \\ & L & \\ & & \end{bmatrix}^{-1} \left\{ \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} - \begin{bmatrix} p\psi_{am} \\ p\psi_{bm} \\ p\psi_{cm} \end{bmatrix} - \begin{bmatrix} r_a & & \\ & r_b & \\ & & r_c \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \right\} \tag{12}$$

The calculation equation of excitation potential is as follows:

$$\begin{aligned} e_a(x_e) &= p\psi_{am}(x_e) = \frac{d\psi_{am}(x_e)}{dt} \cdot \frac{dx_e}{dx_e} \\ &= v\frac{d\psi_{am}(x_e)}{dx_e} = vp_x\psi_{am}(x_e) \end{aligned} \tag{13}$$

Similarly, the following will be obtained.

$$e_b(x_e) = vp_x\psi_{bm}(x_e) \qquad e_c(x_e) = vp_x\psi_{cm}(x_e)$$

For the convenience of analysis, without considering the influence of armature reaction magnetic field on the inductance, the change rate of the inductance over time is:

$$pL = \frac{dL}{dt} = \frac{dL}{dt}\frac{dx}{dx} = \frac{dL}{dx}\frac{dx}{dt} = vp_xL \tag{14}$$

The tangential force produced by the reciprocity of the primary and secondary magnetic field is:

$$\begin{aligned} f_{total} &= \begin{bmatrix} i_a & i_b & i_c \end{bmatrix} \begin{bmatrix} p_x\psi_{am}(x_e) \\ p_x\psi_{bm}(x_e) \\ p_x\psi_{cm}(x_e) \end{bmatrix} + \\ &\frac{1}{2}\begin{bmatrix} i_a & i_b & i_c \end{bmatrix} p_x \begin{bmatrix} L_{aa}(x_e) & L_{ab}(x_e) & L_{ac}(x_e) \\ L_{ba}(x_e) & L_{bb}(x_e) & L_{bc}(x_e) \\ L_{ca}(x_e) & L_{cb}(x_e) & L_{cc}(x_e) \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \\ &+ \frac{dW_{PM}}{dx_e} \end{aligned} \tag{15}$$

The dynamic model diagram of PMLSM is shown in Figure 2. In the diagram, K_T stands for the electromagnetic force constant; e is permanent magnet excitation potential matrix, L is the inductance matrix, and R is the resistance matrix.

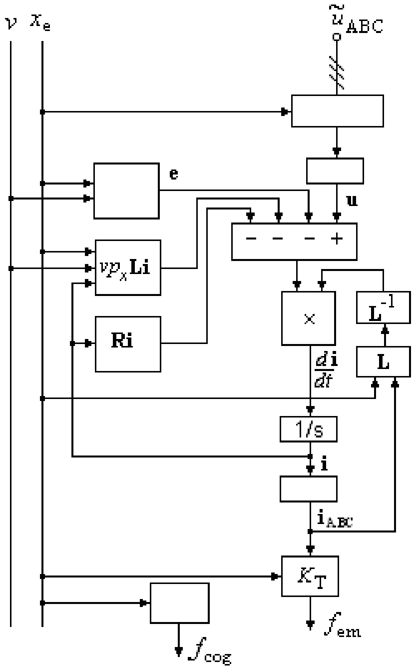

Figure 2. Dynamic model block of PMLSM.

III. CALCULATION AND ANALYSIS OF PMLSM INDUCTANCE

The inductance parameter consists of Self-inductance and mutual inductance and it is the basic parameter of the motor. Considering the special structure of PMLSM, especially the influence of end effects, this paper uses the magnetic field perturbation method to calculate the inductive energy through building the finite element model of PMLSM by finite element analysis method [16].

A. Prototype Parameters of PMLSM

The prototype of PMLSM is a short-primary long-secondary action-primary unilateral structure type, and its parameters are shown in Table I.

TABLE I.
PARAMETERS OF PMLSM

Items [units]	Value
Tooth picth [mm]	13
Slot pitch [mm]	13
Air-gap length [mm]	5
Pole pitch [mm]	39
PM height [mm]	7
PM width [mm]	27
Axial length [mm]	120
Rated thrust force (N)	500

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B. Finite Element Model

The physical model of PMLSM with a short-primary long-secondary type is shown in Figure 3.

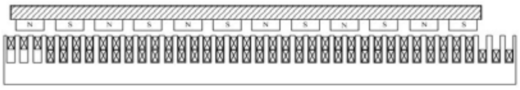

Figure 3. Physical model of PMLSM.

Based on electromagnetic simulation software named Magnet, the finite element model of PMLSM is built, shown in Figure 4.

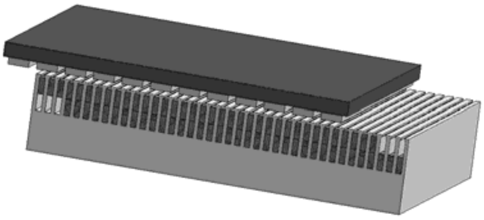

Figure 4. Finite element model of PMLSM.

Figure 5 shows the two-dimensional subdivision with adaptive subdivision method.

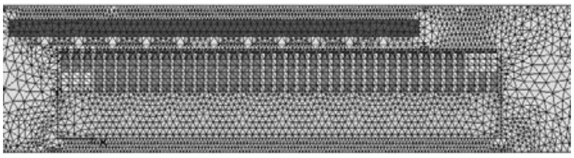

Figure 5. Two-dimensional subdivision of PMLSM.

Figure 6 shows the distribution of magnetic field lines of PMLSM in a certain time.

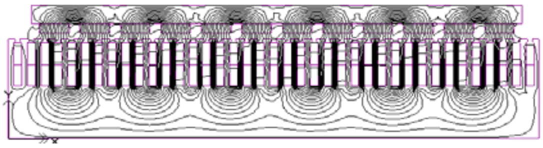

Figure 6. Distribution of magnetic field lines of PMLSM.

Based on the finite element model, the inductance parameters of PMLSM are calculated.

And then the calculation values were contrasted with testing values.

B. Calculation and Testing of Inductance Parameters

In the process of calculation and testing, each move of selection secondary $L_{step}=n/\tau$, where n is the calculated steps within one polar distance. When testing, the sinusoidal AC passes into the three-phase winding. Its frequency of is 50Hz, and the amplitude is 24.5V. The voltage at each time point and its corresponding current is collected by digital oscilloscope DL7450, and then the self-inductance of three phase winding is obtained by calculation.

When the air-gap of PMLSM is 5mm, 8mm, and 12mm, the corresponding self-inductance is calculated and tested respectively. Figure 7 shows the change curve of PMLSM self-inductance of each phase with the primary and secondary position change after calculation and testing when the air-gap is 5mm.

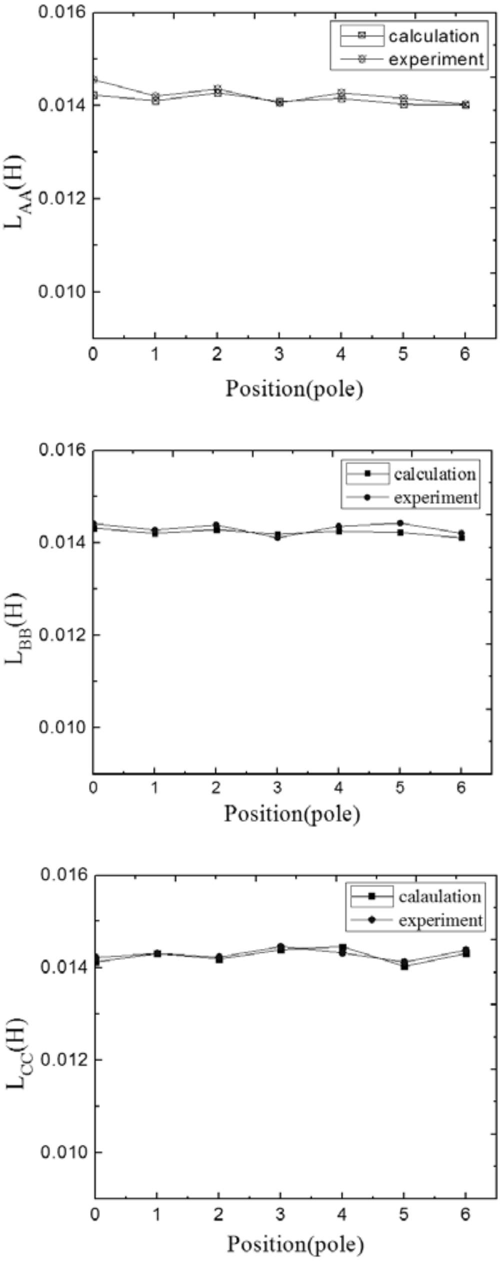

Figure 7. Self-inductance (Air-gap is 5mm).

Table II shows the calculated and measured values of self-inductance with different air-gap.

It can be seen from Figure 7 and Table II that in a certain range, the size of self inductance is not sensitive to changes of the air-gap in length; when then primary is completely within the range of the secondary, the relative position of the primary changes, but the inductor doesn't change.

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TABLE II.
AIR-GAP EFFECT ON THE SELF-INDUCTANCE

Air-gap (mm)	Methods	L_{AA} (H)	L_{BB} (H)	L_{CC} (H)
5	Calculate	0.01413	0.01415	0.01411
	Measure	0.01409	0.01412	0.01408
8	Calculate	0.01399	0.01392	0.01401
	Measure	0.01396	0.01397	0.01398
12	Calculate	0.01387	0.01383	0.01381
	Measure	0.01381	0.01387	0.01384
Note: primary and secondary in fully coupled.				

C. Calculation and Analysis of Mutual Inductance

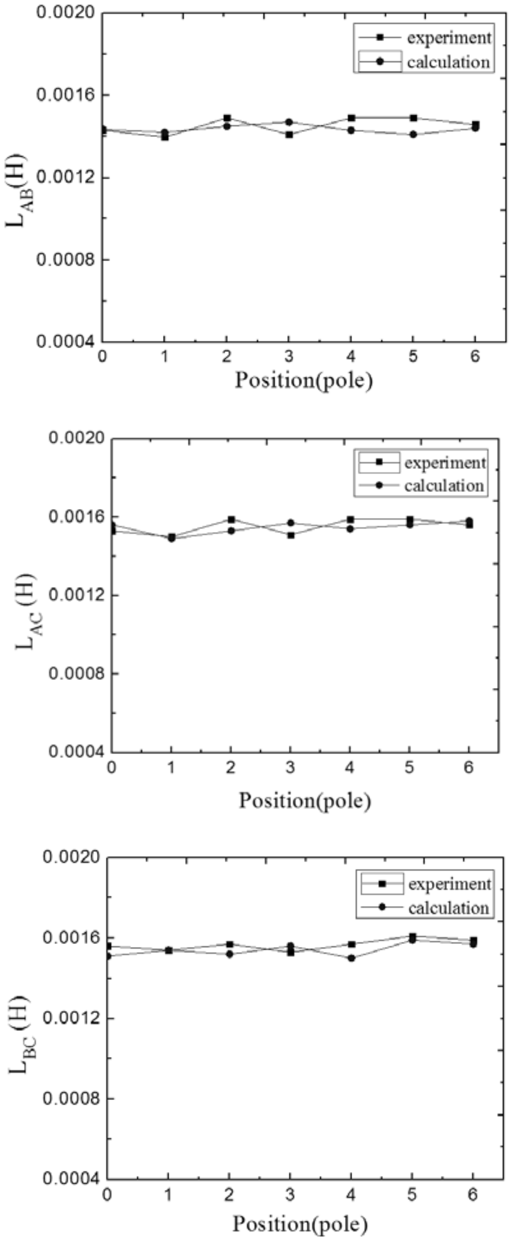

Figure 8. Mutual-inductance (Air-gap is 5mm).

For the calculation and testing of the mutual inductance, pass a sinusoidal AC of which the frequency is 50Hz and the amplitude is 24.5V into a one phase winding, collect the induced voltage and current at each time point of the other two phase winding, and then calculate its mutual inductance. Move the relative position of the primary, the mutual inductance curve to the primary relative displacement is obtained. When the air-gap of PMLSM is 5mm, the calculated value and measured value are shown in Figure 8.

In addition, when the air-gap of PMLSM is 20mm and ∞, the mutual inductance parameters are calculated and tested, as is shown in Table III.

TABLE III.
CALCULATION AND EXPERIMENT VALUES OF MUTUAL-INDUCTANCE

Air-gap (mm)	Methods	L_{AB} (H)	L_{AC} (H)	L_{BC} (H)
20	Calculate	-0.0011	-0.00135	-0.00136
	Measure	-0.001151	-0.001432	-0.001432
∞	Calculate	-0.000913	-0.00107	-0.00106
	Measure	-0.000979	-0.001113	-0.001111
Note: primary and secondary in fully coupled.				

It can be seen from Figure 8 and Table III that the smaller the air-gap is, the larger the mutual inductance will be. Because of the open primary and end effects, the mutual inductance of the three phases is asymmetric, and LAC and LBC is approximate, both of which are bigger than that of LAB.

IV. CALCULATION AND ANALYSIS OF PMLSM EXCITATION FLUX

A. Theoretical Analysis of Excitation Flux

The broken magnetic circuit of PMLSM, the half filled terminal socket of primary winding and the disconnected winding distribution altogether make the electromagnetic parameters unbalanced.

So flux linkage and EMF of the motor being non sinusoidal, whose accurate mathematical model is hard to set up through analytical ways [17, 18].

Excitation flux, having no relation with the position of the secondary, is produced by the cross-linking between the excitation field and the primary winding. Excitation flux is important physical quantities to analyze the characteristics and control of PMLSM.

It is great significance to get the excitation flux and confirm the relationship between excitation flux and the position of the secondary.

The equation of flux calculation is:

$$\phi = \int_a \vec{B}\cdot d\vec{a} = \int_a rot\vec{A}\cdot d\vec{a} = \oint_l \vec{A}\cdot d\vec{l} \qquad (16)$$

Considering the effect of the longitudinal ends of the primary and secondary, the primary winding of each phase coil excitation flux is obtained with the secondary in different locations. Then the excitation flux of each winding is got by the superposition of flux of each coil in the windings. If the solution method is the magnetic vector potential, the average value of each component is taken.

The synthesis flux linkage of each phase winding is:

$$\psi_p(x_e) = \sum_{i=1}^{n_c} \psi_i(x_e) \tag{17}$$

where, n_c is the turns of each phase winding.

B. Excitation Flux Caculation by FEM

The PMLSM finite element model is build to calculate and analyze the excitation flux and the EMF of each winding.

Figure 9 shows the three-phase simulation flux linkage of PMLSM. Figure 10 shows the EMF of PMLSM.

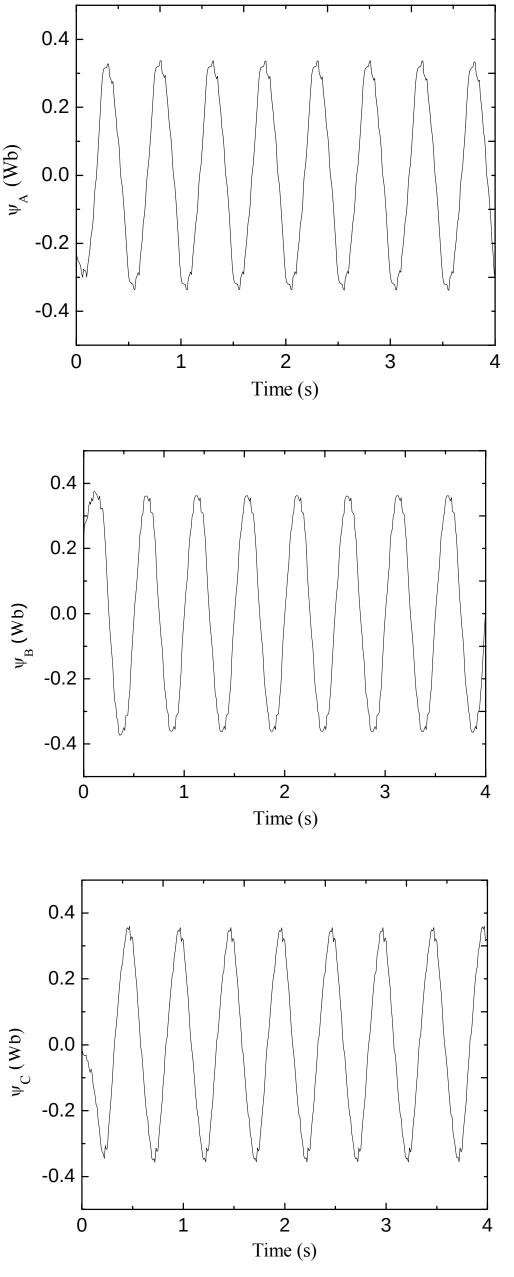

Figure 9. Three-phase simulation flux linkage of PMLSM.

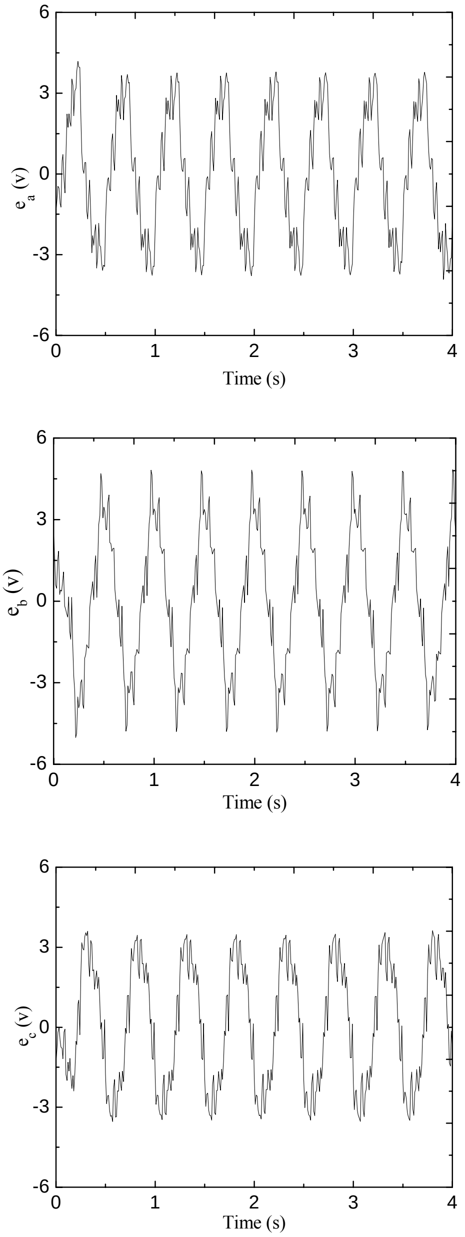

Figure 10. Three-phase EMF of PMLSM.

As Figure 9 and Figure 10 shown, the excitation flux linkage of every loop of the primary windings of all phases when the secondary is at different positions is worked out through magnetic vector potential method, then the excitation flux linkage of the windings of all phases can be got by adding the flux linkage of the loops. Two conclusions are drawn: one is that the three-phase flux linkage is asymmetrical; the other is that the three-phase flux linkage is non-sinusoidal, with abundant harmonics. Of course, the EMF of PMLSM is non-sinusoidal because of the non-sinusoidal of the excitation flux, having rich harmonic component.

In order to analyses the harmonic component of the flux linkage of PMLSM, FFT is used. And the analysis result is shown in Figure 11 and Table IV.

Figure 11 shows the analysis of A phase flux linkage by FFT. Table IV shown the harmonic component of A phase flux linkage with FFT.

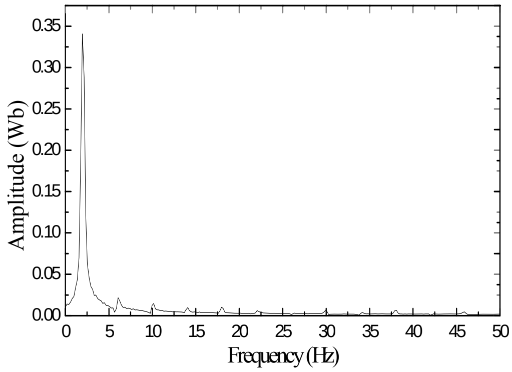

Figure 11. FFT analysis of A phase flux linkage.

TABLE IV.
HARMONICS COMPONENT OF A PHASE FLUX LINKAGE WITH FFT

Harmonic number	Amplitude	Percentage
1	0.34110	85.64%
5	0.02307	5.79%
9	0.01501	2.77%
13	0.00906	2.27%
17	0.01006	2.53%

V. CONCLUSION

The structural differences of PMLSM compared with traditional rotary motor are that the primary core is open, and the winding is not continuous, which lead to the non-sinusoidal of voltage, current, flux and variability of parameters, so it is difficult to precisely build the model with analytical method.

Based on this, from PMLSM reality, this paper analyzes the structural and running characteristics of PMLSM, takes the asymmetry of three-phase winding of PMLSM into account and builds the space state model of PMLSM. After the finite element calculation and actual measurement of its inductance parameters, it shows that when the primary and the secondary is completely coupling, the self and mutual inductance parameters of PMLSM do not change with changing position of the primary and the secondary; the length of the air-gap shows little impact on self inductance parameters, but has significant impact on the mutual inductance parameter. Specifically, when primary is within secondary domain, the self inductance is not sensitive to the length of the air gap, the three-phase self inductance being almost symmetrical. But mutual inductance is affected by the length of the air gap, the shorter the air gap, the larger the mutual inductance and the three-phase inductance are asymmetric, L_{AC} and L_{BC} being very close and much bigger than L_{AB}. Furthermore, the excitation flux of PMLSM is calculated and analyzed by finite element method. And two conclusions are drawn: one is that the three-phase flux linkage is asymmetrical; the other is that the three-phase flux linkage is non-sinusoidal, with abundant harmonics.

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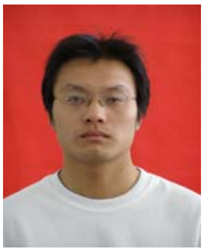

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