Design of linear phase shift transformer and analytical calculation of no-load electromagnetic field

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Abstract. Linear phase-shift transformer is a new type of transformer, which can be used in multi-rectifier and multi-inverter system. Taking the design of a linear phase-shifting transformer for multiple superimposed inverters as an example, a layered magnetic field analysis model of the linear phase-shifting transformer is established. Firstly, the primary side slot is treated as a smooth structure, then the model is layered and the current density of primary side is calculated by the single Fourier method. Taking into account the boundary conditions of the transformer, the distribution expressions of the vector magnetic potential and the magnetic flux density in the solution region are derived, the relative permeability function of the air gap is established and the influence of the slot effect on the air gap electromagnetic field is calculated. In this paper, the distribution of electromagnetic field without load is calculated. Finally, the feasibility of the method is verified by simulation, which provides basis for the following engineering calculation and optimization design of linear transformer.

Keywords: LINEAR phase-shifting transformer, Electromagnetic field

1. Introduction
Linear phase-shift transformer is a new type of transformer, which can be used in multi-rectifier and multi-inverter system. Taking the design of a linear phase-shifting transformer for multiple superimposed inverters as an example, a layered magnetic field analysis model of the linear phase-shifting transformer is established. Firstly, the primary side slot is treated as a smooth structure, then the model is layered and the current density of primary side is calculated by the single Fourier method. Taking into account the boundary conditions of the transformer, the distribution expressions of the vector magnetic potential and the magnetic flux density in the solution region are derived, the relative permeability function of the air gap is established and the influence of the slot effect on the air gap electromagnetic field is calculated. In this paper, the distribution of electromagnetic field without load is calculated. Finally, the feasibility of the method is verified by simulation, which provides basis for the following engineering calculation and optimization design of linear transformer.

At present, finite element method and analytical method are mainly used to solve the electromagnetic performance of motor. Comparing the two, the finite element method has the advantages of high precision and complex structure processing, but the calculation speed is slow and time consuming, and the division of mesh will affect the calculation accuracy. The analytical method can clearly reflect...
the relationship between the size parameters and the electromagnetic parameters, which is faster and less computational, and is more conducive to the initial design and optimization of the motor.

In combination with the structure characteristics of this new type of transformer, this paper selected based on the method of literature [2], expand, shown in figure 1, for linear phase shifting transformer, hierarchical electromagnetic field analysis model is established, analyzes the harmonic current and harmonic magnetic field, vertical direction of magnetic field are calculated by linear transformer, considering the slot effect, establish the air gap relative permeance ratio function to gauge and the influence of the cogging effect, finally get the vertical direction of the magnetic flux density;The feasibility of this method is verified by finite element method, which provides important basis for the design optimization of ontology in the future.

2. Analytical calculation of electromagnetic field when the original side current acts alone

2.1. Calculation of current density of the original side

In this paper, the single - dimensional Fourier series method [3] is used to solve the current density. For the convenience of calculation, the following assumptions are given:

(1) The original side is 3 phases, the number of slots per pole is 4, the secondary side is 12 phases, the number of slots per pole is 2, the whole distance winding and the double-layer winding are distributed;

(2) The transformer slot is a rectangular open slot, the number of turns of single-layer winding in series is, the height of single-layer winding of each slot is, the slot distance is, and the slot width is;

(3) The original side is connected to the three-phase symmetrical current source, and the skin effect in the wire is ignored. The current in each turn of the three-phase wire is as follows:

\[ i_a = \sqrt{2} I \cos(\omega t), i_b = \sqrt{2} I \cos(\omega t - \frac{2\pi}{3}), i_c = \sqrt{2} I \cos(\omega t + \frac{2\pi}{3}). \]

Substitute \( J_a = \frac{N_i a}{b_i h_e}, J_b = \frac{N_i b}{b_i h_e}, J_c = \frac{N_i c}{b_i h_e} \) into:
According to the formula, the original side can obtain the current layer synthesized by multiple traveling wave currents.

2.2. Poisson’s equation for electromagnetic field

In the linear transformer, the schematic diagram of the original side winding is shown in Figure 2. For the convenience of calculation, the linear transformer must be regarded as an ideal state and the following assumptions are made:

1. The current density and vector magnetic potential have only z-axis components;
2. The original side and the auxiliary side of the core tooth groove area is temporarily treated as a smooth structure without slots;
3. The magnetic circuit of the transformer does not exist saturation;
4. The magnetic field changes with time sine.

The transformer is stratified into five layers, from bottom to top: core layer, primary side current layer, air gap, secondary side current layer, core layer.

(1) For the motor air gap section \( \sigma = 0 \), so:

\[
\frac{\partial^2 A_{1z}}{\partial x^2} + \frac{\partial^2 A_{1z}}{\partial y^2} = 0
\]  

(3)

(2) For the original part, the current in the slot is equivalent to the current layer, and the current density is \( J_{1z} \), so

\[
\frac{\partial^2 A_{2z}}{\partial x^2} + \frac{\partial^2 A_{2z}}{\partial y^2} = -\mu_0 J_{1z}
\]  

(4)

The separation of variables method was used to solve the equation (3).

\[
A_{1z} = \sum_{k=1,5,7,\ldots}^{\infty} [(A_{1k} e^{\frac{k\pi}{\tau}} + B_{1k} e^{\frac{-k\pi}{\tau}}) \cos(\frac{k\pi}{\tau} x)]
\]  

(5)

\[
A_{2z} = \sum_{k=1,5,7,\ldots}^{\infty} (A_{2k} e^{\frac{k\pi}{\tau}} + B_{2k} e^{\frac{-k\pi}{\tau}} + \frac{\mu_0 J_{1z}}{k^2 \pi^2}) \cos(\frac{k\pi}{\tau} x)
\]  

(6)

2.3. The boundary conditions of the original electromagnetic field and the solution of harmonic coefficients

1. The interface connection conditions for scoring are as follows:

\[
\frac{\partial A_{1z}}{\partial y} \bigg|_{y=-h} = \frac{\partial A_{2z}}{\partial y} \bigg|_{y=-h}
\]  

(7)
\[ A_{2z} \big|_{y=-h} = A_{2z} \big|_{y=-h} \]  
\[ A_{2z} \bigg|_{y=H_1+h} = 0 \]  
\[ A_{2z} \bigg|_{y=H_1-h} = 0 \]  

Four equations can be obtained from the boundary conditions, \( m_k = e^{-\frac{k\pi}{r}} \), \( n_k = e^{-\frac{k\pi}{r+(H_1)}} \). Let the four equations be written as a matrix \( Q_k \times R_k = I_k \):

\[ A_{1z} = \sum_{k=1,5,7}^{\infty} \left[ (A_{1k} e^{-\frac{k\pi}{r}} + B_{1k} e^{-\frac{k\pi}{r}}) \cos\left(\frac{k\pi}{r} x\right) \right] \]  
\[ A_{2z} = \sum_{k=1,5,7}^{\infty} \left( A_{2k} e^{-\frac{k\pi}{r}} + B_{2k} e^{-\frac{k\pi}{r}} + \frac{\mu_0 J_k}{k^2} \tau^2 \right) \cos\left(\frac{k\pi}{r} x\right) \]

### 3. The effect of tooth groove on electromagnetic field

As defined \( \beta(y) = \frac{B_{\text{max}} - B_{\text{min}}}{2B_{\text{max}}} \), the air gap permeability of a single slot can be obtained by using allow-transformable [2]:

Thus:

\[ \lambda(x, y) = \begin{cases} 
1 - \beta(y) - \beta(y) \cos\left(\frac{\pi x}{0.8b_0}\right), & |x| \leq 0.8b_0 \\
1, & 0.8b_0 \leq |x| \leq 0.5b_r 
\end{cases} \]  
\[ \lambda_1(x, y) = [1 - \beta(y) - \beta(y) \cos\left(\frac{\pi x}{0.5b_r}\right)] \]  
\[ \lambda_2(x, y) = [1 - \beta(g - y) - \beta(g - y) \cos\left(\frac{\pi x}{0.5b_r}\right)] \]

It can be obtained that the magnetic induction intensity at any point in the air gap during no-load time is:

\[ B_{1z} = B_{1z} \lambda_1 \lambda_2 \]
4. Analytical calculation and finite element verification

This paper takes a linear transformer as an example to analyze electromagnetic field under no load condition. The transformer adopts the whole-distance winding and the original side is supplied with three-phase alternating current. The sample parameters are shown in Table 1.

According to the distribution density of magnetic field lines in FIG. 5, a pair of magnetic poles is generated in the transformer under the action of the original side current. Most of the magnetic field lines pass through the transformer teeth.

| Symbol | Implication                              | Numerical value |
|--------|------------------------------------------|-----------------|
| \( l \) | Total length of transformer (mm)         | 216             |
| \( d \) | width of air gap (mm)                   | 0.3             |
| \( H_s \) | Slot depth (mm)                         | 24              |
| \( h_c \) | Single-layer winding thickness (mm)     | 12              |
| \( b_s \) | Slot width (mm)                         | 12              |
| \( b_r \) | pitch (mm)                              | 18              |
| \( \tau \) | Polar distance (mm)                    | 108             |
| \( Nl \) | ampere-turns (A)                        | 1000            |

**Table 1. Linear transformer sample parameter table**

![Distribution of magnetic field lines](image1.png)

**Figure 3. Distribution of magnetic field lines**

It is found in FIG. 5 that the relative permeability ratio of the air gap fluctuates at the tooth groove and presents periodicity.

![Current density waveform](image2.png)

**Figure 4. Current density waveform**
The center line of the air gap is the radial magnetic density of the electromagnetic field at the point, as shown in FIG. 6. By comparing the finite element simulation results with the analytical results, it is found that the two are basically consistent, which verifies the feasibility of the magnetic field density calculation method. In the solution of current density, the current density is directly equivalent to the single-layer thickness of the tooth groove area, and the current density is relatively large, so the finite element simulation result is larger than the analytical method in the tooth. In addition, in the calculation, only finite order can be selected for calculation, especially high order harmonics will be ignored, and in order to simplify the calculation process, some approximate processing is done, which also affects the accuracy of the results.

![Figure 5. Relative permeability ratio waveform of air gap](image1)

Figure 5. Relative permeability ratio waveform of air gap

![Figure 6. 100 radial magnetic density at the center line of Harmonic Air gap](image2)

Figure 6. 100 radial magnetic density at the center line of Harmonic Air gap

5. Conclusion
In this paper, based on the hierarchical analytical model, using the Fourier series method for linear phase shift transformer magnetic field analysis and calculation, the air gap relative permeance ratio function to modify the original edge slot on straight line transformer flux density, the influence of the finite element results verify the feasibility of the method, significantly reduced the amount of calculation, the optimization of linear phase shift transformer ontology design provides the basis.
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