Design and Application of Linear Phase-shifting Transformer

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Abstract. In power conversion equipment, the Phase-shifting Transformer plays an important role in reducing harmonic pollution and improving the quality of output waveform. Based on the principle and structure of linear motor, a linear phase-shifting transformer is designed in this paper to overcome the disadvantages of the traditional phase-shifting transformer with complicated winding structure and difficult expansion. This paper introduces the basic principle of the linear phase-shifting transformer, deduces the relevant formulae of the electromagnetic design of the linear phase-shifting transformer, carries out the finite element simulation, applies the linear phase-shifting transformer to the multiple stacked inverter system, and proves the effectiveness of the designed linear phase-shifting transformer.

1. Introduction

The percentage of electricity used by users after conversion has become one of the main indicators of a country's technological progress. As an energy converter, transformer has significant influence on the performance and efficiency of power conversion system, and has been widely used in various sectors and fields of national economy. With the development and widespread application of transformers, a large number of loads working at different voltages flood into the power grid, and the harmonic pollution of the public power grid has become increasingly serious, which not only affects the stability of the power grid, but also adversely affects its performance [1]. The phase-shifting transformer adopts multiple transformation technology, which not only can effectively reduce harmonics and grid pollution, but also improves the quality of output waveform and output performance [2, 3]. However, the windings of the traditional phase-shifting transformer are complicated and difficult to process, and the utilization rate of the winding is low. The complex structure of the circular phase-shifting transformer is not conducive to expansion, and the air-gap magnetic field is difficult to control [4].

In this paper, a linear phase-shifting transformer is designed based on the simple structure of linear motor. It overcomes the traditional phase-shifting transformer winding’s shortcomings, such as design complex, impossibility to achieve precise turn ratio and expand with difficulty. It is proved that the output harmonic of the linear phase-shifting transformer is reduced and the quality of the output waveform is improved.

2. Basic principle of linear phase shift transformer

Linear phase-shifting transformer have the similar structure and working principle with linear motor. The difference is that the linear motor moves in a straight line and the length of the stator and rotor is different. While the linear phase-shifting transformer is fixed, the length of the stator and rotor (primary
and secondary side) is the same. The cores of primary and secondary side are embedded with 3-phase and n-phase windings, and by changing the value of N, the flexible selection of phase-shifting angle can be realized [5].

Similar to the working principle of linear motor, the primary edge of linear phase-shifting transformer is connected with three-phase alternating current. When the three-phase current changes with time, the air-gap magnetic field moves in a straight line according to the phase sequence of A, B and C, which is the traveling wave magnetic field. The traveling wave magnetic field is running at a speed of \( V_0 = 2f \tau \text{ (m/s)} \) [6]. The coil of secondary side generates the induced electromotive force under the traveling wave magnetic field cutting, and exports the three-phase Alternating current at the secondary side through the designed winding way. Because both the primary and the secondary sides are fixed and speed is equal to zero. \( s = \frac{V_0 - V}{V} = \frac{V_0}{V} = 1 \), The linear phase-shifting transformer can be regarded as a linear motor with slip of 1.

3. Electromagnetic design of linear phase shift transformer

Electromagnetic design is the basis of the whole transformer manufacturing. Electromagnetic calculation is to check whether the electromagnetic design scheme meets the design's requirements and the material consumption is relatively low according to the relationship between the motor design data, electromagnetic parameters, performance and other physical quantities [7]. The linear phase-shifting transformer designed in this paper is based on the principle of linear induction motor. The principle of induction motor, linear motor and transformer should be taken into account in electromagnetic calculation. The original data of the design is: rated power: 1100W; rated voltage: 220V; rated current: 5A; rated frequency: 50Hz.

3.1. Electromagnetic load selection

The selection of electromagnetic load is usually based on a large number of practice to sum up the experience curve for designing selection. The linear phase-shifting transformer is based on the principle of linear motor, and its electromagnetic load is selected within the range of conventional motor design. In order to control the saturation of magnetic circuit caused by harmonic flux, low flux density is generally adopted in the design, which is not only beneficial to reduce the temperature rise of the motor, but also beneficial to reduce the electromagnetic noise. Therefore, the air gap flux density \( B_\delta \) and the primary electrical load \( AS \) were selected as \( B_\delta = 1.5T \) and \( AS = 84000A/m \).

3.2. Selection of main dimensions
The main dimension of the linear phase-shifting transformer refers to the effective dimension of electromagnetic induction for energy conversion, that is to say, the length and width of the iron core are the main dimension. The pole log of the linear phase-shifting transformer designed in this project is \( p = 1 \). Length of primary core (equivalent to the perimeter of the inner diameter of the stator core of an ordinary rotating induction motor):

\[
L = 2\pi r + 2b_e
\]  

Where, \( b_e \) represents the width of the two teeth at the edge of the primary core.

Calculate the apparent power of the transformer:

\[
P' = m_1 E_1 I_1
\]  

Where, \( m_1 \) represents the primary phase number, \( E_1 \) represents the primary winding phase potential, and \( I_1 \) represents the primary winding phase current.

Then, the width of the primary core (equivalent to the axial length of the stator core of an ordinary rotating induction motor) is obtained:

\[
2a = \frac{0.25p'}{0.707a_w B_0 (AS)^2 f pK_{w1}}
\]  

Where \( 2a \) represents the core width of the primary, \( k_{w1} \) represents the primary winding coefficient, and \( a_w \) represents the reduction coefficient of the primary winding.

### 3.3. Winding design

The linear phase-shifting transformer designed in this project is a 3/12 phase-shifting transformer for multiple inverters. Both primary and secondary sides are double-layer windings with 12 slots in each layer. Winding pitches respectively are: the primary edge using the whole pitch winding \( (y_1 = \tau) \), secondary edge with long distance and short distance windings \( (y_1 = 5\tau/6 \text{ and } y_1 = 7\tau/6) \).

The magnetic flux of each air gap in the transformer is:

\[
\Phi_\delta = \frac{2}{\pi} B_\delta \tau 2a
\]  

The number of turns per phase of primary winding in series is:

\[
w_1 = \frac{k_B U_1}{a_w A4.44 f \Phi_\delta K_{w1}}
\]  

Where \( k_B \) is the inverse potential coefficient, \( k_B = \frac{E_1}{U_3} \).

According to the principle of selecting the groove type and size in the design of rotating induction motor, the size of the groove type can be obtained as follows, and the current density is taken as \( \Delta_1 = 9 \times 10^6 \text{ (A/m}^2) \).

\[
I_{st} = \frac{p\tau(AS)}{m_1 w_1}
\]  

\[
A = \frac{I_{st}}{\Delta_1}
\]  

\[
Q = \frac{N_2 n d_0^2}{3s f}
\]
\[ Q_s = (h_t - h_0)b_s \]  

(9)

\[ S \times f = \frac{N_1 nd_0^2}{Q_3} \]  

(10)

\[ b_t = t_1 - b_s \]  

(11)

Where, \( I_{st} \) represents no-load closing current, \( A \) represents the cross-sectional area of the primary winding wire, \( Q_s \) represents the slot area required by the primary winding, \( S \times f \) represents the slot full rate, \( b_t \) represents the primary tooth width, and \( N_1 \) represents the number of turns of the primary winding.

In order to avoid the second type of transverse edge effect caused by different widths of primary and secondary edges, the length and width of primary and secondary edges of the linear phase-shifting transformer designed in this project are equal.

The number of turns of the secondary side winding can be estimated from the transformer design data:

\[ U_2 = \frac{N_2 U_1}{N_1} \]  

(12)

4. Finite element simulation analysis

According to the results of the electromagnetic design of the linear phase-shifting transformer in section 3, a simulation model was built in Maxwell. The three-dimensional physical model of the linear phase-shifting transformer and the distribution of each phase winding are shown in figure 3, in which the upper half is the primary side of the transformer and the lower half is the secondary side of the transformer. The primary edge uses the whole distance winding, while the secondary edge uses the combination of the long distance winding and the short distance winding. The main parameters of the simulation model are as follows: the output phase voltage \( U_A = U_B = U_C = 220V \); Output frequency \( f=50Hz \); Output power \( P=1100W \); Original edge phase number \( m_1=12 \); Secondary edge phase number \( m_2 = 12 \); the original edge slot number \( Z_1 = 12 \); side edge slot number \( Z_2 = 12 \); \( p=1 \); Slot spacing \( d=18mm \); Core length \( L=216mm \); Core height \( H=40mm \); Primary and secondary side air gap 0.3mm; Close stack thickness 108mm.

**Figure 3.** Winding distribution of linear phase shifted transformer

In this section, the finite element simulation is carried out to verify the multiplex inverter system based on linear phase-shifting transformer, and the output voltage is analyzed by FFT. Then, this paper has compared of no-load, rated load, 20%-load, 50%-load, etc. According to the parameter calculation and model method mentioned above, the inverse system is analyzed.
Figure 4. Voltage waveform under no-load

Figure 5. FFT analysis of voltage under no-load

Figure 6. Voltage waveform under 80% load
Several experiments are carried out in this paper, but the simulation diagram is only listed three times. The all results are shown in the following table:
### Table 1. Simulation results under different load

| Load situation | Fundamental voltage amplitude (V) | Harmonic component |
|----------------|----------------------------------|--------------------|
| no-load        | 234.9                            | 9.23%              |
| 40%-load       | 230.5                            | 4.69%              |
| 60%-load       | 228.4                            | 3.95%              |
| 80%-load       | 225.8                            | 3.41%              |
| rated load     | 223                              | 3.02%              |

It can be seen from the simulation results that the output voltage harmonic content of the inverter system is less than 5% when different loads are connected and no filter is equipped. The harmonic content is small and the output waveform quality is good, which meets the requirements.

### 5. Conclusion

In order to overcome the traditional phase-shifting transformer winding’s shortcomings such as design complex, impossibility to achieve precise turn ratio and expand with difficulty, this paper deduces the electromagnetic design formula of linear phase-shifting transformer, designs a new type of linear phase-shifting transformer, and applies the linear phase-shifting transformer to the multi-stacked inverter system. The following conclusions are drawn:

1. The effectiveness of the electromagnetic design method and winding structure design method for linear phase-shifting transformer proposed in this paper are verified by finite element simulation.
2. The multiple superposition system based on linear phase-shifting transformer can output three-phase alternating current with low harmonic, which has better load capacity and can improve the output performance of power conversion device.
3. The linear phase-shifting transformer is designed based on the simple structure of linear motor. It is easy to produce modular and easy to expand.

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