Design of linear phase shifting transformer based on linear motor

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Abstract. In this paper, a linear phase shifting transformer based on linear motor is studied. The transformer is composed of four groups of three-phase full-bridge inverter system and a linear core. The DC power supply can be converted into three-phase alternating current through the inverter system and the linear phase shifting transformer. Compared with the traditional phase-shifting transformer, the linear phase-shifting transformer is easy to expand, easy to connect, and has better heat dissipation. The simulation results show that this scheme is feasible.

Keywords: phase shifting transformer, linear motor, multiple superposition.

1. Introduction
The inverter system is most often used to convert DC and AC in daily life. The multi-superposition inverter system used in this paper is mainly characterized by small harmonic content, high efficiency and large output power [1, 2].

Phase-shifting transformer is a special transformer. Its main principle is to superposition and synthesize multiple groups of potential into an approximate sinusoidal step wave by phase-shifting. Phase shifting transformer can not only carry out electrical isolation, but also eliminate harmonics to a certain extent. At present, there are two main types of phase-shifting transformers: core pillar type phase-shifting transformer and circular phase-shifting transformer [3, 4, 5, 6]. However, due to the influence of structure, the winding structure design of these two types of phase-shifting transformer is complex, and it is not suitable to expand, so when the phase number increases, the design and manufacture of transformer will become difficult. Based on the linear motor structure, this paper designs a new linear phase shifting transformer, compared with the traditional transformer, it has the following advantages:

1) Simple winding structure, easy to expand.
2) The air gap magnetic field is easy to adjust and can be very small.
3) Expanded area, better heat dissipation.

2. Principle of linear phase shift transformer
The basic working principle of linear phase shifting transformer is as follows:
2.1. Basic working principle

In this paper, we study the linear phase shifting transformer is similar to the linear motor, Fig. 1 shows the basic structure of transformer, the former vice edge structure is basically the same, in the middle of nine double groove, both ends respectively for three and A half filling tank, A logarithmic is 1, the original edge with four groups of three phase bridge inverter circuit for input, A, B, C three-phase winding distribution. When the primary side inputs three-phase symmetric AC, a traveling wave magnetic field will be generated in the air gap, and then the secondary side induces three-phase AC voltage and current.

![Figure 1. Basic structure of linear transformer](image1.png)

2.2. Working principle of inverter circuit

Fig. 2 shows the system consisting of four three-phase bridge rectifier circuits in parallel and a linear transformer. The transformer is input by three-phase inverter circuit composed of four groups of IGBTs. The control mode is 180°. Each group outputs 6 stepped waves, and each group lags 15° in turn [7].

![Figure 2. Structure of the multiple stack system](image2.png)
The conduction order of IGBT is shown in Table 1, and the superimposed synthesis is 24 step waves [8]. Since the transformer itself is perceptual, it has the function of filtering [9].

| Sequence | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 |
|----------|----|----|----|----|----|----|----|----|----|----|----|----|
| IGBT     | T1 | T7 | T13| T19| T2 | T8 | T14| T20| T3 | T9 | T15| T21|
| Sequence | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
| IGBT     | T4 | T10| T16| T22| T5 | T11| T17| T23| T6 | T12| T18| T24|

3. Parameter design of linear phase shifting transformer

3.1. Main size design
Refer to the design method of linear motor [10]:

Core length of original side (equivalent to the inner diameter circumference of the stator core of rotary motor):

\[ L = 2p \tau + 2b_c \]  \hspace{1cm} (1)

Calculated power of induction motor:

\[ P' = m_1 E_1 I_1 \]  \hspace{1cm} (2)

Rated power of induction motor:

\[ P_N = m_1 U_{N1} I_1 \eta_N \cos \phi_N \]  \hspace{1cm} (3)

Where, \( P_N \) is the rated power, \( P' \) is the calculated power, and considering the short-distance coefficient, distribution coefficient and winding reduction coefficient of the fundamental wave, there are:

\[ E_1 = 4K_{Nm} N f K_{dp} \Phi_{\delta_{\text{max}}} \]
\[ = a_w K_{Nm} K_{dp} N f (D \tau \frac{2}{\pi} B_\delta) \]  \hspace{1cm} (4)

Flux per pole:

\[ \Phi = B_\delta a_s \tau I_{ef} \]  \hspace{1cm} (5)

Induction motor line load:

\[ A = \frac{2mN I_1}{L} \]  \hspace{1cm} (6)

In combination with (1), (2), (3) and (5), it can be obtained:

\[ LD = \frac{\pi P_N K_E}{a_w K_{Nm} K_{dp} \eta_N f \tau B_\delta \cos \phi_N} \]  \hspace{1cm} (7)

In combination with (1), (2), (3), (4), the following can be obtained:

\[ D = \frac{0.25 P'}{0.707 a_w B_\delta A \tau^2 \alpha f p K_{dp}} \]  \hspace{1cm} (8)

The primary and secondary cores of the transformer are laminated with DW465-50 silicon steel sheets, and the "knee point" of the magnetization curve is about 1.8T. In order to avoid the influence...
of core saturation on the transformer performance, the air-gap magnetic density $B_{\delta}$ is set at 0.8T in this paper.

Considering the size of transformer, select $A = 20000 \, A/m$, $K_x = 0.8$, $K_w = 1.11$, $\tau = 126 \, mm$, to calculate $K_w = 0.9659$, $\alpha_w = 0.5$, and substitute the data to obtain the preliminary design $D = 0.122 \, m$, $L = 315 \, mm$.

3.2. Calculation of winding parameters

![Winding diagram of model winding](image)

Figure 3. Winding diagram of model winding

Reference winding parameter design of rotary motor:

Effective value of primary phase voltage:

$$U_i = \frac{8}{3\sqrt{2}} \eta U_d \quad (9)$$

Number of series conductors per phase on primary side:

$$N_\phi = \frac{\eta \cos \varphi LA}{m_i I_{KW}} \quad (10)$$

It can be known that the number of turns in series for each phase of the primary side is:

$$N_i = \frac{N_c Z_i}{2m_i a_i} \quad (11)$$

Where, $\eta$ is the efficiency, $I_{KW}$ is the working current of the induction motor, $N_c$ is the number of turns per coil on the original side, and $a_i$ is the number of parallel branches.

Bringing in the relevant data, we can get $N_i = 271, N_i = 319$. There is a certain error between the actual value $B_{\delta}$ and the selected value, so it needs to be fine-tuned after the finite element simulation to meet the requirements.

4. Preliminary finite element verification of the model

4.1. No-load Verification

Combined with the no-load magnetic field simulation results in FIG. 4, the magnetic flux generated by the primary side current can be divided into three parts according to the coupling degree of the magnetic flux.
1) the flux produced by the primary side current and not coupled by the secondary side is called flux leakage.
2) the magnetic flux produced by the primary side current and not fully coupled by the secondary side is the incomplete coupled magnetic flux.
3) magnetic flux produced by primary side current, fully coupled by secondary side, main coupled magnetic flux.

The three-phase output results of finite element simulation are as follows:

**Figure 4.** Magnetic force diagram of no-load simulation result

**Figure 5.** No-load output voltage

**Figure 6.** No-load output current
FIG. 5 and FIG. 6 are the simulation waveforms of output voltage and output current of linear phase-shifting transformer in no-load condition. It can be seen from the figure that three-phase output is all stepped wave, which is consistent with theoretical analysis. The output voltage is slightly unbalanced due to the open ends of the linear transformer and the influence of the "half-filled slot".

$$A + B - C + A - B + A - B + A + B - C + A - B +$$

4.2. Load verification

FIG. 8 shows the air-gap flux density diagram of the linear transformer under rated load.

Figure 7. "half-filled slot" linear transformer

Figure 8. Load air gap flux density diagram
FIG. 9 and FIG. 10 are the three-phase output voltage and current of the linear phase-shifting transformer at rated load, both of which are sinusoidal waves, consistent with theoretical analysis.

5. Conclusion
In this paper, a linear phase shifting transformer is designed based on linear motor. The design process and finite element simulation are given. The following conclusions are drawn:

1) The results show that the harmonic content of linear phase shifting transformer is 9.38% in no-load condition and 1.23% in rated load condition, and the filtering effect is significantly improved.

2) Compared with other phase-shifting transformers, wiring is convenient and winding structure is simple. Because of the special structure of the linear phase-shifting transformer, the phase-shifting Angle is more convenient to realize and the efficiency is easier to improve.

3) Due to the influence of "half-filled trough" and longitudinal side effect, the amplitude of three-phase output voltage is slightly different, which is related to the length of air gap, pole distance and pole logarithm, etc. By adjusting these parameters, the influence on the performance of linear phase shifting transformer can be reduced.
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