Design and Simulation Analysis of Fractional Slot five Phase Induction Motor

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Abstract. In induction motor, fractional slot winding can not produce high quality traveling wave field, its application is limited. There are only a few researches on the fractional slot poly phase induction motor. In this paper, a five phase induction motor with fractional slot is designed by traditional magnetic circuit method, the mathematical model is given, and two kinds of winding forms are designed. The correctness of the motor design is verified by simulation. After that, the research of fractional slot five phase induction motor laid the foundation of studies on fractional slot five phase induction motor.

1. Introduction
Fractional slot winding has a good application prospect in permanent magnet motor [1]. However, in induction motor, fractional slot winding can not produce high quality traveling wave field, its application is limited [2]. There are only a few researches on the fractional slot poly phase induction motor. Based on the traditional magnetic circuit method, this paper designs the fractional slot five phase induction motor, solves some key parameters, simulates the model by the finite element method, and analyzes the starting performance of the motor.

2. Electromagnetic design of fractional slot five phase induction motor
According to the performance requirements of a motor [3], the power of the motor is not less than 1.5KW, and the rated speed is n = 1500r / min. Design output power PN = 2.5KW, number of phases M = 5, phase voltage U = 220V, frequency f = 50Hz, number of poles P = 2.

2.1. Determination of main dimensions.
The main dimension refers to the empirical value of the size of the effective part of the induction energy conversion of the motor, or by properly selecting the electromagnetic load a (line load) and Bσ (air gap magnetic density), and then selecting the appropriate λ (main dimension ratio) with reference to the recommended data, Di1 and lef can be calculated, and the outer diameter of the stator can be estimated by KD (stator inner diameter ratio). According to the center height of the frame, it is necessary to take into account the reasonable nesting of silicon steel sheet, and to modify the original calculated size 4].

After calculating, Stator outer diameter D1 = 175mm, stator inner diameter Di1 = 98mm, stator core length L = 105mm, stator slot number Z1 = 30, Select stator material D23_50. The stator slot is pear shaped with the following dimensions:
hs0 (mm): 0.8, hs1 (mm): 0.837, hs2 (mm): 10.6,
bs0 (mm): 3.2, bs1 (mm): 6.1, bs2 (mm): 8.1

Air gap length $\delta = 0.5\text{mm}$, outer diameter of squirrel-cage rotor $D_2 = 97\text{mm}$, inner diameter $d_2 = 38\text{mm}$.

2.2. Magnetic circuit calculation.
The magnetic circuit calculation is to calculate the magnetic flux density and magnetic potential drop of each section of the magnetic circuit according to the main magnetic flux of each pole required to generate the full load electromotive force of the motor, so as to obtain the required excitation magneto motive force and excitation current. The purpose of magnetic circuit calculation is to determine the magnetizing force or exciting magneto motive force necessary to produce the main magnetic field, and then calculate the exciting current and no-load characteristics of the motor. Through the magnetic circuit calculation, it can also check whether the selection of the flux density of each part of the motor is appropriate.

For the three-phase asynchronous motor, the end leakage self-inductance coefficient $L_{el}$ of a single coil can be calculated by the empirical formula. Different from that, the $L_{el}$ of five phase asynchronous motor should be calculated in a discrete way: the coil end is divided into several current elements, and the magnetic field generated by the current element is calculated according to Biot Savart theorem; the magnetic field at each point of the end is the superposition of each current element at that point, and the self-leakage flux chain and the corresponding self-inductance coefficient of the leakage flux are obtained accordingly. For details, refer to [5].

2.3. Loss and performance calculation.
After the main dimensions, air gap, stator and rotor winding and core are designed, the working performance calculation and starting performance calculation shall be carried out to facilitate the comparison of performance indexes specified in the design specification or technical conditions [6]. On this basis, necessary adjustments shall be made to the previous design. The starting performance of induction motor mainly refers to the influence of starting torque and starting current on the corresponding rated value. China's national standards have specific regulations on the starting performance of various types of induction motors.

2.4. Design flow.
See Appendix for details.

3. Design calculation results

3.1. Design results.
According to the speed, from the formula $np=60f$, the pole number of the motor is 4. The number of stator slots is 30.

As we know, $q = \frac{z}{2pm} = b + \frac{c}{d}$, so $b = 1, c = 1, d = 2$. It is determined that the motor is a fractional slot motor.

Considering the symmetry of the stator structure, the double-layer winding is adopted. In order to simplify the calculation, one branch is set. The turns of the single-layer winding are 39 and the wire diameter is 0.72mm.

Define the number of parallel branches is $a = 1$. In Figure 2, the stator five phase winding is represented by A, B, C, D and E respectively. The specific connection of a phase winding has been clearly shown (A and a respectively represent the head and the end). The other four phase winding can be divided and connected according to the 72° spatial electrical angle of A, B, C, D and E.

There are two winding distribution schemes of fractional slot structure, as shown in Table 1 below. The winding distribution in the stator is shown in the following figure (coarse in and fine out):
Figure 1. Stator arrangement of fractional slot motor with 30 slots

of stator and different winding forms.

The electromagnetic calculation and optimization calculation results of induction motor are shown in Table 1.

| stator inner diameter (cm) | Air gap length (cm) | iron core length (cm) | Number of wires per slot | spacer factor |
|---------------------------|--------------------|-----------------------|--------------------------|--------------|
| 9.83                      | 0.035              | 12.37                 | 78                       | 77.8%        |

Table 1. Electromagnetic calculation and optimization results of induction motor.

| Number of parallel wires & wire diameter (mm) | Flux density of stator teeth (T) | Rotor tooth flux density (T) | Air gap flux density (T) | Stator current density (A/mm²) |
|-----------------------------------------------|----------------------------------|-----------------------------|--------------------------|-------------------------------|
| 1-ф0.72                                      | 1.52                             | 1.69                        | 0.62                     | 5.39                          |

| Current density of rotor bar (A/mm²) | thermal load (A/cm·A/mm²) | Copper weight of stator winding (kg) | Aluminum weight of cast aluminum rotor (kg) | Steel core silicon steel sheet weight (kg) |
|-------------------------------------|-----------------------------|-------------------------------------|---------------------------------------------|-------------------------------------------|
| 1.26                                | 1321.4                      | 3.37                                | 1.48                                        | 21.73                                     |

| Full load efficiency | power factor | Maximum torque multiple | Starting current multiple | Starting torque multiple |
|----------------------|--------------|-------------------------|---------------------------|-------------------------|
| 80.4%                | 0.81         | 2.15                    | 3.60                      | 2.87                    |

3.2. Mathematical model

The stator circuit is selected according to A, B, C, D, e five-phase winding, and the Rotor Circuit is selected according to the Cage Rotor’s actual Mesh Circuit [7].

Stator voltage equation:

\[ U_s = R_s i_s + \frac{d\psi_s}{dt} \]  (1)

Rotor voltage equation:

\[ U_r = R_r i_r + \frac{d\psi_r}{dt} \]  (2)

Stator flux equation:

\[ \psi_s = \psi_{ss} + \psi_{sr} \]  (3)

\[ \psi_{ss} = L_{ss} i_s \]  (4)
\[ \psi_{sr} = L_{sr}i_r \]  
(5)

\[ L_{ss} \] is for the stator inductance Matrix, rotor flux equation:

\[ \psi_r = \psi_{rr} + \psi_{rs} \]  
(6)

\[ \psi_{rr} = L_{rr}i_r \]  
(7)

\[ \psi_{sr} = L_{rs}i_s \]  
(8)

The stator-rotor phase voltage vector, the stator-rotor phase current vector and the stator-rotor flux vector are expressed as follows:

\[ U_s = [u_{s1}, u_{s2}, u_{s3}, u_{s4}, u_{s5}]^T \]  
(9)

\[ I_s = [i_{s1}, i_{s2}, i_{s3}, i_{s4}, i_{s5}]^T \]  
(10)

\[ U_r = [u_{r1}, u_{r2}, u_{r3}, u_{r4}, u_{r5}]^T \]  
(11)

\[ I_r = [i_{r1}, i_{r2}, i_{r3}, i_{r4}, i_{r5}]^T \]  
(12)

\[ \psi_s = [\psi_{s1}, \psi_{s2}, \psi_{s3}, \psi_{s4}, \psi_{s5}]^T \]  
(13)

\[ \psi_r = [\psi_{r1}, \psi_{r2}, \psi_{r3}, \psi_{r4}, \psi_{r5}]^T \]  
(14)

Based on the winding configuration, the stator and Rotor Resistance matrices are defined as follows:

\[ R_s = \begin{bmatrix} r_s & 0 & 0 & 0 & 0 \\ 0 & r_s & 0 & 0 & 0 \\ 0 & 0 & r_s & 0 & 0 \\ 0 & 0 & 0 & r_s & 0 \\ 0 & 0 & 0 & 0 & r_s \end{bmatrix} \]  
(15)

\[ R_r = \begin{bmatrix} r_r & 0 & 0 & 0 & 0 \\ 0 & r_r & 0 & 0 & 0 \\ 0 & 0 & r_r & 0 & 0 \\ 0 & 0 & 0 & r_r & 0 \\ 0 & 0 & 0 & 0 & r_r \end{bmatrix} \]  
(16)

\[ L_{ss} \] is the stator inductance Matrix, \( L_{ls} \) and \( L_{ms} \) are the leakage inductance and mutual inductance of the stator winding, \( \theta = \frac{2\pi}{5} \), \( L_{rr} \) is the rotor inductance Matrix, \( L_{sr} \) and \( L_{rs} \) are the stator-rotor mutual inductance Matrix.

\[ L_{ss} = L_{ls} + L_{ms} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} + \begin{bmatrix} 1 & \cos(\theta) & \cos(2\theta) & \cos(3\theta) & \cos(4\theta) \\ \cos(\theta) & 1 & \cos(\theta) & \cos(2\theta) & \cos(3\theta) \\ \cos(2\theta) & \cos(\theta) & 1 & \cos(\theta) & \cos(2\theta) \\ \cos(3\theta) & \cos(2\theta) & \cos(\theta) & 1 & \cos(\theta) \\ \cos(4\theta) & \cos(3\theta) & \cos(2\theta) & \cos(\theta) & 1 \end{bmatrix} \]  
(17)
\[
L_{rr} = L_{tr} + L_{mr} = \begin{bmatrix}
1 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 1 \\
\end{bmatrix}
\begin{bmatrix}
1 & \cos (\theta) & \cos (2\theta) & \cos (3\theta) & \cos (4\theta) \\
\cos (\theta) & 1 & \cos (\theta) & \cos (2\theta) & \cos (3\theta) \\
\cos (2\theta) & \cos (\theta) & 1 & \cos (\theta) & \cos (2\theta) \\
\cos (3\theta) & \cos (2\theta) & \cos (\theta) & 1 & \cos (\theta) \\
\cos (4\theta) & \cos (3\theta) & \cos (2\theta) & \cos (\theta) & 1 \\
\end{bmatrix}
\]

\(L_{sr} = L_{sr}^T = \begin{bmatrix}
\cos (\theta_r) & \cos (\theta + \theta_r) & \cos (2\theta + \theta_r) & \cos (3\theta + \theta_r) & \cos (4\theta + \theta_r) \\
\cos (4\theta + \theta_r) & \cos (\theta_r) & \cos (\theta + \theta_r) & \cos (2\theta + \theta_r) & \cos (3\theta + \theta_r) \\
\cos (3\theta + \theta_r) & \cos (4\theta + \theta_r) & \cos (\theta_r) & \cos (\theta + \theta_r) & \cos (2\theta + \theta_r) \\
\cos (2\theta + \theta_r) & \cos (3\theta + \theta_r) & \cos (4\theta + \theta_r) & \cos (\theta_r) & \cos (\theta + \theta_r) \\
\cos (\theta + \theta_r) & \cos (2\theta + \theta_r) & \cos (3\theta + \theta_r) & \cos (4\theta + \theta_r) & \cos (\theta_r) \\
\end{bmatrix}
\]

Among them, \(L_{sr}\) and \(L_{rs}\) are the mutual inductance matrix of stator and Rotor, \(\theta_r\) is the angle between stator and rotor.

Through the above equation, the mathematical model of five-phase motor is established, which is convenient to solve and calculate.

4. **Simulation of motor based on finite element method**

Based on Ansoft Maxwell [8], it is assumed that voltage source is used for power supply, the voltage is five phase 220V AC, the phase difference is 72° in turn, the frequency is 50Hz, and the five phase power supply is set as follows.

\[V_a = 220 \times \sin(2\pi50\times\text{time})\]  \(\text{(20)}\)

\[V_b = 220 \times \sin(2\pi50\times\text{time}-2\pi5)\]  \(\text{(21)}\)

\[V_c = 220 \times \sin(2\pi50\times\text{time}-4\pi5)\]  \(\text{(22)}\)

\[V_d = 220 \times \sin(2\pi50\times\text{time}-6\pi5)\]  \(\text{(23)}\)

\[V_e = 220 \times \sin(2\pi50\times\text{time}-8\pi5)\]  \(\text{(24)}\)

Therefore, the five phase induction motor is simulated and analyzed. Under the same power supply, the simulation results of the two motors are as follows:
As shown in Figure 2, in the initial stage of starting, the torque fluctuation of type I winding is uniform, and the starting torque is relatively small, the steady-state time is short, and the fluctuation is small.

**Figure 2.** Comparison of no-load electromagnetic torque.
As shown in Figure 3, the rotor moment of inertia of the motor is set to 0.0178kg. m², there will be a disturbance at the initial stage of motor starting, and the type II winding disturbance is about 300r/min, and the type I winding disturbance is about 80r/min (it may be caused by fractional slot, the specific reasons will be analyzed later). The type I winding reaches stable speed in about 0.44s, and the overshoot is small when it reaches stable state; The type II winding reaches stable speed in about 0.48s, and its overshoot is relatively large.

Figure 3. Comparison of starting speed of motor.
Figure 4. Comparison of no-load stator current (five phases).
As shown in Figure 4 and Figure 5, before reaching the steady state, the torque fluctuation of type I winding is even, and the starting torque is relatively small, the time to reach the steady state is short, and the fluctuation is small. The stator current harmonics of the two motors are large (probably due to the deviation of theoretical calculation value of winding inductance, to be analyzed in detail).

**Figure 5.** Comparison of no-load stator current (phase A)
Figure 6. Comparison of induction electromotive force (five phases)
As shown in Figure 6 and figure 7, before reaching the steady state, the induced electromotive force of winding I, motor will have a process of overshoot, and then the induced electromotive force will reach the steady state, and the induced electromotive force of winding II motor will transition smoothly.
As shown in Figure 8, after reaching the steady state, the distribution of air gap magnetic field intensity of winding 1 is close to the sinusoidal distribution, but the peak of transient magnetic field intensity between teeth is large, and that of winding 2 is close to the sinusoidal distribution, with small peak, which is generally stable.

**Figure 8.** Comparison of magnetic field intensity amplitude in air gap under steady state

**Fig. 9** comparison of distribution of magnetic field lines of motor in steady state
As shown in Fig. 9, after reaching the steady state, the magnetic lines of the two motors are evenly distributed.

5. Conclusion
In this paper, a five phase induction motor with fractional slot is designed by traditional magnetic circuit method, the mathematical model is given, and two kinds of winding forms are designed. The correctness of the motor design is verified by simulation. By comparing the characteristics of winding I and winding II in no-load starting process, the speed overshoot of type I winding is small, the ripple coefficient of type II winding is small, and the air gap magnetic field and starting torque of type 2 winding are good. After that, the research of fractional slot five phase induction motor laid the foundation.

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Appendix

START

Assuming the electromotive force coefficient KE, saturation coefficient Ks, efficiency and corresponding iteration error

Magnetic circuit calculation

Re hypothesis KE

Ks Comparison between calculated value and initial value

Small error

Impedance calculation in normal operation

Full load current calculation

Re hypothesis Ks

Large error

η Comparison between calculated value and initial value

Small error

Efficiency calculation

η Comparison between calculated value and initial value

Large error

Calculation of Cosδ, Sn, Tmax

Assumed starting current Ist

Impedance calculation at start-up

Starting current calculation

Re hypothesis Ist

Large error

Ist Comparison between calculated value and initial value

Small error

Calculation of starting torque

END