Magnetic Potential Analysis of Five-Phase Induction Motor During Two Phase Fault

Yinpeng Zhou\textsuperscript{a}, Jinghong Zhao\textsuperscript{*} and Yuanzheng Ma\textsuperscript{b}

School of Electrical Engineering, Naval University of Engineering, Wuhan, China

\textsuperscript{*}Corresponding author e-mail: zhaojinghong@163.com, \textsuperscript{a}1246936000@qq.com, \textsuperscript{b}1362039810@qq.com

Abstract. The main research object of this paper is the change of magnetic potential produced by five-phase induction motor when it runs without two phase, the magnetic potential of five-phase Induction Motor which lacks two phases is compared with that of normal operation by using the method of synthetic current and the theory of double rotating magnetic field, by Simulink simulation analysis, to explain the influence of the motor stability when the motor is running without phase in detail.

1. Introduction

The continuous development of modern power electronic technology has put forward higher requirements for motor control system. Five-phase motor is widely used in the military, shipping, aerospace and other high-caliber fields because of its higher reliability, greater freedom and greater flexibility in control. Consequently, the stability of the motor control system is of great significance because the five-phase motor often works in the severe environment, high danger and very important occasions, such as aerospace, military, ship, etc. But five-phase motor will work in the state of phase absence due to various factors, which not only seriously affects the stability of the system and its performance, but also leads to frequent accidents. Once the phase fault occurs, the fundamental wave and harmonic current of the remaining phases will inevitably change, which will have a great impact on the space synthetic magnetic field, resulting in the decline of the performance. Therefore, accurate and effective magnetic potential analysis is a necessary prerequisite for performance analysis and fault-tolerant control strategy research when the motor phase losses.

For the five-phase induction motor, when the motor occurs asymmetric phase fault, the analysis method is relatively complex, and its calculation needs to be carried out on all phases to obtain a complete result. At present, the main methods to analyze the steady-state performance of five-phase induction motors include phase coordinate method, symmetric component method, multiloop method and electromagnetic field finite element method. Among them, Toliyat applied phase coordinate method to study the fault of a branch of stator winding and end ring; Y. Lee studied the effect of inter-turn short circuit on motor performance by using inter-turn short circuit coefficient; X.R. Chang used phase coordinate method to establish a differential equation to analyze the influence of rotor guide bar fault on the system. But the symmetric component method is very difficult to solve, so it is rarely used to analyze the phase fault of the multiphase motor. Z. c. Liu used the multi-loop method to establish the motor equation and studied the motor performance when the rotor guide bar failed, but it needs to solve a large number of variable coefficient equations, and the calculation is very complicated. T.M. Jahns
used the symmetric component method to completely analyze the performance of the n-phase induction motor when the n-1 phase is powered on, but the transformation matrix between the phase component and the order component of the symmetrical component method needs to change according to the position and quantity of the missing phase. Compared with the traditional analytical method, Mingzhong Qiao uses finite element simulation to calculate the torque ripple of a five-phase induction motor with different winding structures when the field and road coupling is applied, but the finite element calculation takes a long time. It can be seen from the synthesis of the existing methods that the fault analysis of the five-phase Induction Motor in the absence of phase is still based on the circuit calculation. In order to make up for the deficiency of the existing magnetic potential analysis methods, based on the double magnetic field rotation theory, the magnetic potential of a five-phase induction motor operating without two phases is analyzed by using the synthetic current in this paper.

2. Magnetic potential analysis of five-phase induction motor under normal operation

The distribution of air-gap magnetic field of inverter-powered multiphase induction motor is affected by many factors, which can be divided into space harmonic and time harmonic according to the harmonic generation. Once the fault occurs, the fundamental wave and harmonic current of the remaining phases will inevitably change, which will have a great impact on the space synthesis magnetic field, and lead to the decline of motor performance. Therefore, accurate and effective magnetic potential analysis is a necessary prerequisite for phase fault analysis and fault-tolerant control.

In this paper, the magnetic potential variation of five-phase induction motor in the absence-phase fault is analyzed by using the synthetic current method. From the winding structure of the five-phase motor, it can be seen that the five-phase induction motor is only composed of a set of windings, and the difference between windings is \( \frac{2\pi}{5} \) of the electric angle. Therefore, only the asymmetric phase absence of either one or two phases will occur. In normal operation of five phase induction motor, the Axis of phase a winding is taken as the reference axis, and the Fourier series expansion of magnetic potential of phase a winding is as follows:

\[
N_{as}(\phi) = \sum_{n=1}^{\infty} \frac{4A}{n\pi} \sin\left(\frac{n\pi}{2}\right) \cos(n \phi) \tag{1}
\]

The phase winding functions of b, c, d and e can be obtained by successively lagging, and on the basis of the phase winding functions of \( \frac{2\pi}{5}, \frac{4\pi}{5}, \frac{6\pi}{5}, \frac{8\pi}{5} \). As follows:

\[
N_{bs}(\phi) = \sum_{n=1}^{\infty} \frac{4A}{n\pi} \sin\left(\frac{n\pi}{2}\right) \cos\left(n\left(\phi - \frac{2\pi}{5}\right)\right) \tag{2}
\]

\[
N_{cs}(\phi) = \sum_{n=1}^{\infty} \frac{4A}{n\pi} \sin\left(\frac{n\pi}{2}\right) \cos\left(n\left(\phi - \frac{4\pi}{5}\right)\right) \tag{3}
\]

\[
N_{ds}(\phi) = \sum_{n=1}^{\infty} \frac{4A}{n\pi} \sin\left(\frac{n\pi}{2}\right) \cos\left(n\left(\phi - \frac{6\pi}{5}\right)\right) \tag{4}
\]

\[
N_{es}(\phi) = \sum_{n=1}^{\infty} \frac{4A}{n\pi} \sin\left(\frac{n\pi}{2}\right) \cos\left(n\left(\phi - \frac{8\pi}{5}\right)\right) \tag{5}
\]

Since only the fundamental wave is considered in this paper, so in equations (1)-(5): \( n=1, A = \frac{N_{\phi}}{2n_p}, n_p \) is the pole logarithm of the motor, and \( N_{\phi} \) is the series function of the stator windings of each phase of the motor.

Suppose the expression of the excitation current in the winding of the five-phase induction motor is as follows:

\[
i_{as} = \sum_{m=1}^{\infty} i_m \cos(m\omega_e t) \tag{6}
\]
\[ i_{ds} = \sum_{m=1}^{\infty} l_m \cos[m(\omega_e t - \frac{2\pi}{5})] \]  
(7)

\[ i_{cs} = \sum_{m=1}^{\infty} l_m \cos[m(\omega_e t - \frac{4\pi}{5})] \]  
(8)

\[ i_{ds} = \sum_{m=1}^{\infty} l_m \cos[m(\omega_e t - \frac{6\pi}{5})] \]  
(9)

\[ i_{es} = \sum_{m=1}^{\infty} l_m \cos[m(\omega_e t - \frac{8\pi}{5})] \]  
(10)

Where, \( \omega_e \) is the fundamental wave angular frequency, and \( l_m \) is the amplitude of m-order harmonic excitation current.

The magnetic potential generated by each phase current can be expressed as:

\[ f_a = N_{as}(\phi)i_{as} = \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \frac{4A}{\pi^2} l_m \sin\left(\frac{n\pi}{2}\right) \cos(m\omega_e t) \cos(n\phi) \]  
(11)

\[ f_b = N_{bs}(\phi)i_{bs} = \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \frac{4A}{\pi^2} l_m \sin\left(\frac{n\pi}{2}\right) \cos[m(\omega_e t - \frac{2\pi}{5})] \cos[n(\phi - \frac{2\pi}{5})] \]  
(12)

\[ f_c = N_{cs}(\phi)i_{cs} = \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \frac{4A}{\pi^2} l_m \sin\left(\frac{n\pi}{2}\right) \cos[m(\omega_e t - \frac{4\pi}{5})] \cos[n(\phi - \frac{4\pi}{5})] \]  
(13)

\[ f_d = N_{ds}(\phi)i_{ds} = \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \frac{4A}{\pi^2} l_m \sin\left(\frac{n\pi}{2}\right) \cos[m(\omega_e t - \frac{6\pi}{5})] \cos[n(\phi - \frac{6\pi}{5})] \]  
(14)

\[ f_e = N_{es}(\phi)i_{es} = \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \frac{4A}{\pi^2} l_m \sin\left(\frac{n\pi}{2}\right) \cos[m(\omega_e t - \frac{8\pi}{5})] \cos[n(\phi - \frac{8\pi}{5})] \]  
(15)

The expression for the resultant air-gap magnetodynamic potential generated by a five-phase symmetrical current is:

\[ f = f_a + f_b + f_c + f_d + f_e = \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \frac{4A}{\pi^2} l_m \sin\left(\frac{n\pi}{2}\right) \begin{cases} \cos(m\omega_e t) \cos(n\phi) \\ + \cos(m(\omega_e t - \frac{2\pi}{5})) \cos(n(\phi - \frac{2\pi}{5})) \\ + \cos(m(\omega_e t - \frac{4\pi}{5})) \cos(n(\phi - \frac{4\pi}{5})) \\ + \cos(m(\omega_e t - \frac{6\pi}{5})) \cos(n(\phi - \frac{6\pi}{5})) \\ + \cos(m(\omega_e t - \frac{8\pi}{5})) \cos(n(\phi - \frac{8\pi}{5})) \end{cases} \]  
(16)

3. Magnetic potential analysis of five-phase induction motor without two-phase operation

Based on the first section of the five-phase induction motor without two-phase operation, the five-phase induction motor without two-phase operation can be divided into two cases: One is an adjacent two-phase break, the other is non-adjacent two-phase break; The two cases need to be studied separately. Firstly, the adjacent two-phase break is taken as the research object and take a and b two-phase as an example. At this point, the winding magnetic potential generated by a and b phases is 0, and the excitation current is 0, while the other phases remain unchanged. Then the current state of the five-phase...
induction motor is that the electrical Angle difference between c, d and e phases is $\frac{6\pi}{5}$, and the electrical Angle difference between c and d phases is $\frac{2\pi}{5}$:

$$N_{ac}(\phi) = 0$$

$$N_{bc}(\phi) = 0$$

$$i_{ac} = 0$$

$$i_{bc} = 0$$

It can be obtained that the magnetic potential generated by the two phases of a and b is 0 as well:

$$f_a = 0$$

$$f_b = 0$$

Then the resultant magnetic potential generated by the absence of a and b phases of the five-phase induction motor is:

$$f = f_c + f_d + f_e = N_{ac}(\phi) i_{cs} + N_{dc}(\phi) i_{ds} + N_{ec}(\phi) i_{es}$$

$$= \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \frac{4A}{n \pi} I_m \sin\left(\frac{n \pi}{2}\right) \left\{ \cos\left[m\left(\omega t - \frac{4\pi}{5}\right)\right] \cos\left[n \left(\phi - \frac{4\pi}{5}\right)\right] \\
+ \cos\left[m\left(\omega t - \frac{6\pi}{5}\right)\right] \cos\left[n \left(\phi - \frac{6\pi}{5}\right)\right] \\
+ \cos\left[m\left(\omega t - \frac{8\pi}{5}\right)\right] \cos\left[n \left(\phi - \frac{8\pi}{5}\right)\right] \right\}$$

The second case is the non-adjacent phase absence. In this paper, the phase absence of a and c is taken as an example, so the electrical angles of mutual difference between b, d, and b, e is $\frac{4\pi}{5}$, and d, e is $\frac{2\pi}{5}$:

$$N_{ac}(\phi) = 0$$

$$N_{bc}(\phi) = 0$$

$$i_{ac} = 0$$

$$i_{bc} = 0$$
It can be obtained that the magnetic potential generated by the two phases of a and c is 0 as well:

\[
\begin{align*}
    f_a &= 0 \\
    f_c &= 0
\end{align*}
\]  

(28)  

(29)  

On this basis, the resultant magnetic potential between the remaining non-adjacent three phases is obtained as follows:

\[
\begin{align*}
    f &= f_b + f_d + f_e = N_b \phi_k_e + N_d \phi_k_d + N_e \phi_k_e \\
    &= \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \frac{4A m}{\pi n} \sin \left( \frac{n \pi}{2} \right) \left\{ \cos \left( m \left( \omega t - \frac{2 \pi}{5} \right) \right) \cos \left( n \left( \phi - \frac{2 \pi}{5} \right) \right) + \cos \left( m \left( \omega t - \frac{6 \pi}{5} \right) \right) \cos \left( n \left( \phi - \frac{6 \pi}{5} \right) \right) \right. \\
    &\quad \left. + \cos \left( m \left( \omega t - \frac{8 \pi}{5} \right) \right) \cos \left( n \left( \phi - \frac{8 \pi}{5} \right) \right) \right\}
\end{align*}
\]  

(30)  

4. Simulation Results

Matlab simulation analysis was conducted based on the above formulas (1) to (16), and the current and resultant magnetic potential of the five-phase induction motor during normal operation were obtained as shown in figure 1, figure 2:

![Figure 1. Current of the five-phase induction motor during normal operation](image-url)
Figure 2. Magnetic potential synthesis diagram of five-phase induction motor

The current, residual three-phase magnetic potential and resultant magnetic potential of the five-phase induction motor without two-phase operation are shown in the figure below. Situation 1: the operation current and magnetic potential of the five-phase induction motor without a and b phases are shown in figure 3-4 below:

Figure 3. The five-phase induction motor lacks the operating current of a and b phases
Figure 4. Magnetic potential synthesis diagram of the five-phase induction motor without a and b phases

Situation 2: the operation current and magnetic potential of the five-phase induction motor lost a and c phases are shown in figure 5-6 below:

Figure 5. The five-phase induction motor lacks the operating current of a and c phases
From the above four simulations, it can be seen from figures 1 and 2 that the resultant magnetic potential of five-phase induction motor in normal operation is a symmetrical circle and the current is continuous and regular, there are obvious differences between adjacent and non-adjacent two-phase circuit breakers. When a and b are absent, the current of c and e two-phase increases obviously, and the magnetic potential is biased to the right, which proves that the magnetic potential produced by c,d and e axes is too biased, in the same way, when the five-phase induction motor is short of a and c phase, the current of b and d axis increases obviously, and the magnetic potential is left.

5. Conclusion
In this paper, synthesis of current method is used to analyze the five phase induction motor is short of a phase and two phase operation of magnetic potential effect on the performance of the motor running, by solving each case motor phase Fourier series expansion of magnetic potential and current of each phase, the phase of magnetic potential and the synthesis of magnetic potential under different fault condition to analyze the change of the motor performance. This method avoids the traditional magnetic potential analysis method to calculate the multifarious. In the case of phase fault of the motor, the phase current and Fourier series expansion formula is just set as 0, and the analysis process is simple and flexible.

The results of magnetic potential analysis show that when the phase fault occurs in the five-phase induction motor, the magnetic potential of all the Times is distorted into the elliptic rotating magnetic potential, and the current is not stable, which will cause the motor to run out of order, get hot and make too much noise.

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