Study of winding inter turn short circuit effect on permanent magnet synchronous motor performance

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Abstract. Single phase winding’s inter turn short circuit is a common fault in permanent magnet synchronous motor; the short circuit will cause the change of the motor performance to various degrees. In this paper, a 70 kW permanent magnet motor is taken as an example, and ANSYS Maxwell software is used to establish the model of permanent magnet synchronous motor. The inter turn short circuit fault is simulated by reducing the number of turns of the coil. With the help of the software’s powerful electromagnetic field analysis ability and post-processing function, the fault influence on stator winding phase current, electromotive force, torque fluctuation and iron loss, copper loss effect are studied; the current signal is extracted to analyze the relationship between the changes and it is concluded that the amplitude of the third harmonic (150 Hz) of the current increases with the increase of the number of inter-turn short circuit of the A-phase stator. The result can provide the basis for early stage fault diagnosis of the inter turn short circuit.

1. Introduction
With the rapid development of power electronics technology and motor control theory, marine electric propulsion has been rapidly promoted and applied. The permanent magnet synchronous motor has the advantages of small size, light weight, small moment of inertia, wide speed regulation range and high reliability, which meets the requirements of propulsion motor application in ship electric propulsion [1].

The permanent magnet synchronous motor consists of three parts: stator, rotor and bearing. The common fault types are rotor broken strip, rotor loss of magnetism, inter-turn short circuit, air gap eccentricity, bearing fault, etc. [2]. If the signal characteristics of the permanent magnet synchronous motor are used, predicting the fault in advance is of great significance for maintaining its normal operation. The inter-turn short circuit of armature winding is one of the important forms of stator winding faults. According to the change of magnetic field caused by inter-turn short circuit faults, the inter-turn short circuit of stator armature winding is divided into three types. The first is single-phase inter-turn short circuit of stator winding, the second is dual-phase inter-turn short circuit of stator winding, and the third is three-phase inter-turn short circuit of stator winding. Among the three types of short circuit faults, single-phase inter-turn short circuit is the most common form of stator winding short circuit faults. This paper mainly studies the inter-turn short circuit. The inter-turn short circuit is a common destructive motor fault. In permanent magnet motors, insulation aging caused by excessive stator winding temperature, insulation damage caused by electromagnetic force on winding coils, and
transient overvoltage caused by inter-turn insulation deterioration during starting and stopping of motors are common winding faults. No matter what form of inter-turn short circuit fault is caused, it will affect the operation of motors. In severe cases, the motor may cause phase-to-phase short circuit faults or even force the motor to stop, causing great danger to the ship operation [3]. Therefore, from the perspective of safety and economy, the fault diagnosis of single-phase turn-to-turn short circuit of motor winding is particularly important, and some achievements have been made.

At present, there are many methods for diagnosing the short circuit fault of the motor winding. Most are based on signal analysis of back EMF, current, axial flux and torque. A Sarikhani proposed a diagnosis method based on back electromotive force method for permanent magnet synchronous motor under stator winding short circuit fault [4]. Time-frequency analysis is a common analysis method in signal processing and is widely used in short-time Fourier transform (STFT) and wavelet transform analysis of fault diagnosis, such as the literature [5,6]. Diagnostic technology combining signal analysis with artificial intelligence has been widely used in motor online monitoring and diagnosis, such as the literature [7,8]. However, the research on performance of permanent magnet synchronous motor under stator winding short circuit fault by model simulation method is relatively rare.

This paper uses a 70 kW variable speed permanent magnet synchronous motor as a model. The fault model of permanent magnet synchronous motor is established by ANSYS Maxwell finite element analysis software, and the performance curve of the motor under normal conditions and different degrees of fault conditions is obtained and analyzed, which provides a basis for fault diagnosis of the motor.

2. Construction of permanent magnet synchronous motor analysis model

2.1. Motor structure and basic parameters

In this paper, the RMxprt and Maxwell 2D modules in ANSYS Maxwell software are used to establish the motor turn-to-turn short circuit fault model and perform simulation analysis. First, the variable speed permanent magnet synchronous motor model is selected in the RMxprt Module, internal parameters such as the stator, rotor and shafting of the motor are input to generate the motor model. Secondly, the model generated by RMxprt is imported into the Maxwell 2D interface, the transient solver and coordinate system type are selected to generate the physical model. Thirdly, the software will automatically complete the steps of boundary conditions, meshing, model drawing, etc., and finally the finite element model of the motor is completed as shown in figure 1. The simulation time and step size are set manually. After simulation analysis, the 2D transient field solution result is finally obtained.

![Finite element model of permanent magnet synchronous motor](image-url)
The research object of this paper is a small marine permanent magnet synchronous motor. The stator core material is DW315, the rotor shaft material is stainless steel, the stator slot adopts pear-shaped groove, and the stator winding connection mode is star connection. The detailed performance and structural dimensions of the motor are shown in Table 1.

| parameter                        | Value       | parameter                        | Value       |
|----------------------------------|-------------|----------------------------------|-------------|
| Stator outer diameter / mm       | 302         | Polar logarithm/pair             | 3           |
| Stator inner diameter / mm       | 210         | Rated voltage / V                | 498         |
| Number of stator slots / one     | 36          | Rated speed / r · min⁻¹           | 1000        |
| Number of turns per slot         | 22          | Rated power / kW                 | 70          |
| Winding layer / layer            | 2           | Rated frequency / Hz             | 50          |

The winding excitation source of the fault model is set as an external circuit when the model is built. In this paper, phase A is set as fault phase. Different fault conditions are simulated by modifying the number of turns in the coil properties under excitations and modifying the size of the stator winding resistance and leakage inductance parameters in the external circuit. Specific parameters are derived from equation (1). In this paper, the number of turns of phA_30 and phARe_30 of phase A coil property is set. The simulation time is set to 0.6 s and the step is 0.0002 s. The simulation is carried out under rated torque condition. The external circuit design of the motor is shown in Figure 2.

![Figure 2. External circuit diagram of finite element simulation.](image)

\[
R_{sc} = \frac{R}{n_1 n_2} n_{sc}
\]  

(1)

In equation (1): \(n_1\) is the number of conductors in a rod, \(n_2\) is the number of total conductor rods, \(n_{sc}\) is the number of short circuit conductors between turns, and \(R\) is the total resistance of windings, \(R_{sc}\) is Intertturn Short Circuit Resistance.

2.2. Basic equations of electromagnetic fields

In order to simplify the finite element calculation of electromagnetic fields, the assumptions are made as follows:

- Ignore the influence of the displacement current;
- The material is isotropic;
- The magnetic permeability of the material is uniform;
- Vector magnetic position Z-axis component is zero.

Under above assumptions, according to the electromagnetic field theory, the two-dimensional transient electromagnetic field boundary value equation [9] of the motor can be obtained as equation (1).
\[
\begin{aligned}
\Omega: & \quad \frac{\partial^2 A_z}{\partial x^2} + \frac{\partial^2 A_z}{\partial y^2} = -\mu J_z + \mu \sigma \frac{\partial A_z}{\partial t} \\
S_1: & \quad A_z = 0 \\
S_2: & \quad \frac{1}{\mu_1} \frac{\partial A_z}{\partial n} - \frac{1}{\mu_2} \frac{\partial A_z}{\partial n} = J_z
\end{aligned}
\] (2)

In equation (2): \(\Omega\) is the solution area; \(S_1\) is the outer boundary of the stator and the inner boundary of the rotating shaft; \(S_2\) is the outer boundary of the permanent magnet; \(A_z\) is the magnetic vector position; \(J_z\) is the conduction current density; \(\mu\) is the magnetic permeability; \(\mu_1, \mu_2\) is the magnetic permeability of the material on both sides of the permanent magnet boundary; \(\sigma\) is the electrical conductivity; \(J_z\) is the equivalent current density of the permanent magnet; \(t\) is the time.

The conditional functional equations transformed from equation (2) are discretized to satisfy the corresponding boundary conditions, and the multivariate equations are solved.

3. Effect of short circuit on motor performance

3.1. Influence of short circuit on stator current and back electromotive force

In this paper, the single-phase turn-to-turn short circuit in the stator is studied by the above finite element modeling method. The Influence of motor stator short circuit turns on motor stator line current and back electromotive force is obtained. Figures 3 and 4 are three-phase current diagrams in normal operation and three-phase current diagrams in A-phase inter-turn short circuit. Table 2 shows influence of different number of winding short circuit turns on motor stator winding current. Table 3 shows the effect of winding short circuit turns on the back EMF of the stator windings.

![Figure 3. Three-phase current diagram in normal state.](image-url)
Figure 4. Three-phase current diagram of a-phase inter-turn short circuit fault.

Table 2. Influence of winding short circuit turns on motor stator winding current.

| Short circuit turns | A phase current I_A/A | B phase current I_B/A | C phase current I_C/A |
|--------------------|-----------------------|-----------------------|-----------------------|
| 0                  | 142.1                 | 142.4                 | 142.7                 |
| 2                  | 142.7                 | 141.2                 | 141.6                 |
| 4                  | 143.4                 | 140.2                 | 140.7                 |
| 6                  | 144.0                 | 139.2                 | 140.0                 |
| 8                  | 144.8                 | 138.4                 | 139.5                 |

Table 3. Influence of winding short circuit turns on back EMF of motor stator windings.

| Short circuit turns | Back EMF of phase A U_A/V | Back EMF of phase B U_B/V | Back EMF of phase C U_C/V |
|--------------------|---------------------------|---------------------------|---------------------------|
| 0                  | 385.3                     | 385.1                     | 384.8                     |
| 2                  | 384.4                     | 388.1                     | 386.0                     |
| 4                  | 383.3                     | 390.6                     | 387.2                     |
| 6                  | 382.0                     | 392.6                     | 388.3                     |
| 8                  | 380.7                     | 394.3                     | 389.3                     |

It can be seen from table 2 that the permanent magnet synchronous motor can still output power in the case of a slight inter-turn short circuit fault. When the motor is in a normal state, the maximum value of the three-phase winding current of the motor differs by less than 1A. The 70 kW variable speed permanent magnet synchronous motor is a double-layer winding with 11 turns per layer. When 4 turns of the motor stator in a slot are short circuited, the three phase currents in the motor are obviously asymmetrical, and the maximum deviation reaches 4 A. This deviation is greater when 8 turns are short circuited. The inter-turn short circuit of phase A winding causes the short circuit of resistance and leakage inductance of phase A winding, which results in the unbalance of three-phase winding of motor.

In order to compare the influence of different short circuit degree between turns on the three-phase current deviation of each stator winding, this paper uses the three-phase current imbalance degree. Its mathematical expression is as below,
where: $\varepsilon$ is the three-phase current imbalance degree, $I_{\text{max}}$ is the maximum phase current, $I_{\text{min}}$ is the minimum phase current. According to the above calculation method, figure 5 shows the influence of the motor short circuit turns on the stator three-phase current unbalance. Similarly, in order to facilitate the comparison of the maximum value of the fault phase (A phase) current, figure 6 shows the effect of the motor short circuit turns on the fault phase (A phase) current maximum.

\[
\varepsilon = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}}} \times 100\%
\] (3)

It can be seen from figure 5 that the three-phase current imbalance degree of the motor stator increases with the degree of the inter-turn short circuit fault, and changes approximately linearly. It can be seen from figure 6 that the three-phase current imbalance degree of the motor stator is the same as the change of the number of short circuit turns, and the maximum value of the fault phase (A-phase) current is also increased with the deterioration of the inter-turn short circuit fault, and shows the feather of approximate linear law.

Table 3 shows that the maximum value of the back EMF of the three-phase winding is less than 1 V under normal condition. When a turn-to-turn short circuit occurs in one slot of the motor stator, the three opposite electromotive forces in the motor also express significant asymmetry. Referring to the above method for calculating the three-phase current unbalance degree, figure 7 shows the influence of the motor short circuit turns on the stator three-phase voltage unbalance. Similarly, in order to facilitate the comparison of the maximum value of the fault phase (A phase) current, figure 8, shows the effect of the motor short circuit turns on the fault phase (A phase) back EMF maximum.

As can be seen in figure 7, the three-phase voltage imbalance of the motor also increases with the degree of failure, and changes approximately linearly.

It can be seen from figure 8 that the electromotive force imbalance degree and the fault phase (A phase) current maximum value are different from the fault degree change, and the fault phase (A phase) back electromotive force maximum value decreases when the fault degree increases conforming to...
approximate linear law.

3.2. Influence of stator turn-to-turn short circuit on output torque

Due to the three-phase asymmetry of the winding current caused by the short circuit fault, a harmonic magnetic field is formed inside the motor, which has an impact on the output performance of the motor. Figures 9 and 10 are motor torque diagrams for normal condition and A-phase inter-turn short circuit respectively.

![Figure 9. The output torque curve of a permanent magnet synchronous motor under rated load at steady state.](image)

![Figure 10. Influence of short circuit turns on stator circuiting core loss of motor.](image)

It can be seen from figure 9 that the motor can reach the steady state quickly after starting, and the torque fluctuates around the steady state value in a small range due to the influence of the air gap magnetic field in the motor. The fluctuation of the torque is mainly caused by two parts. Firstly, the cogging effect, the value of this part of the torque fluctuation is relatively smaller. Secondly, the harmonic magnetic field, which is caused by the winding distribution coefficient and the rotor magnetic field excitation magnetic field, has a relatively larger influence on the torque fluctuation.

In order to analyze the relationship between the number of single-phase turn-to-turn short circuits and the output torque of the motor, the concept of torque fluctuation coefficient is quoted in this paper. The mathematical expression is as below.

\[
\delta = \frac{\sqrt{\sum (T_i - T_a)^2}}{T_a}
\]  

(4)

Where: \( \delta \) is the motor torque fluctuation coefficient; \( T_i \) is the motor instantaneous torque magnitude; \( T_a \) is the average value of the motor torque.

According to the calculation method of the above equation (4), table 4 shows the changes in motor torque average, torque ripple amplitude and torque ripple coefficient when the permanent magnet synchronous motor is running at rated voltage and fixed power angle.
Table 4. Torque change of permanent magnet synchronous motor under rated load.

| Short circuit turns | Torque average / (N·m) | Torque fluctuation amplitude / (N·m) | Torque fluctuation coefficient |
|---------------------|-------------------------|-------------------------------------|-------------------------------|
| 0                   | 592.8                   | 29                                  | 19.7%                         |
| 2                   | 593.8                   | 33                                  | 20.2%                         |
| 4                   | 594.6                   | 37                                  | 22.3%                         |
| 6                   | 595.2                   | 43                                  | 25.1%                         |
| 8                   | 595.6                   | 49                                  | 28.2%                         |

It can be seen from table 4 that the average value of the motor output torque increases with the deterioration of the inter-turn short circuit fault. Taking the 6 turns short circuit as an example, the torque average value increased by 0.4% compared with the non-short-circuit fault state. It can be seen that the influence of the stator’s single-phase turn-to-turn short circuit on the output torque of the motor is not obvious. At the same time, the torque fluctuation amplitude and torque fluctuation coefficient of the motor show a large rising trend.

3.3. Effect of stator turn-to-turn short circuit on loss

Due to the influence of the harmonic magnetic field, losses will occur in the permanent magnet synchronous motor. The losses mainly include: core loss, stator winding copper loss and wind and friction loss. In this paper, the method of time-step finite element calculation is used to accurately calculate the stator core loss of permanent magnet synchronous motor. For a given working frequency, the core loss of silicon steel sheet is generally calculated according to the following equation [5]:

\[
P_v = K_h B_m^2 f + K_r (B_m)^2 + K_i (K_m f)^{3/2}
\]  

(5)

In equation (5) \(K_h, K_r,\) and \(K_i\) are hysteresis loss coefficients, conventional and additional eddy current loss coefficients respectively; \(K_m\) is the magnetic density amplitude. The stator copper loss can be calculated directly from the armature winding current and the stator phase resistance determined at the time of stabilization. Based on the above calculation method, figures 10 and 11 respectively show the influence of the stator phase short circuit turns of the variable speed permanent magnet synchronous motor on the stator core loss and the winding copper loss.

![Figure 11. Influence of the number of short turns on the copper loss of the motor.](image)

It can be seen from figure 10 that as the degree of short circuit of the A phase winding of the motor increases, the stator core loss of the motor has a certain rising trend. However, since the stator core of the motor is in the form of a lamination, the increase magnitude in loss is small. It can be seen from figure 11 that, unlike the change trend of the stator core loss of the motor, the copper loss of the motor decreases when the degree of the short circuit between the turns increases, but it is not obvious. The main reason is that the stator phase resistance is reduced due to the short circuit between the turns of the winding, so that the copper loss of the stator winding has a certain downward trend.

4. Stator current harmonic amplitude analysis
Since the torque, loss and other parameters cannot be directly measured in practical applications, state quantity observation and correlation algorithms are needed, and current measurement is relatively simple. In this paper, the current signal of the A phase winding of the motor is analyzed to obtain the spectrum of the A phase current. Table 5 shows the variation of the amplitude (dB) of the A phase stator current with change of the number of short circuits.

| Table 5. The variation of the harmonic amplitude (dB) of A phase stator current with the number of short circuited turns. |
|---------------------------------------------------------------|
| Frequency          | Normal       | Short circuit 2 | Short circuit 4 | Short circuit 6 | Short circuit 8 |
|---------------------|--------------|-----------------|-----------------|-----------------|-----------------|
| 150Hz               | -26.34       | -22.56          | -18.30          | -13.29          | -10.04          |
| 250Hz               | -16.62       | -15.93          | -15.65          | -15.67          | -15.64          |
| 350Hz               | -24.89       | -23.78          | -24.48          | -23.31          | -23.45          |
| 450Hz               | -40.86       | -38.00          | -42.43          | -38.38          | -41.27          |

It can be seen from table 5 that the amplitude of the third harmonic (150 Hz) increases with the number of short circuit turns between the A-phase stator, while the amplitudes of other frequencies are almost the same.

5. Summary

In this paper, a finite element model of the inter-turn short circuit of the motor is established by changing the number of conductors in the stator slot of the permanent magnet synchronous motor, and the simulation of the motor under normal and different degrees of fault conditions is carried out. The results show that the parameters of phase current, back electromotive force, torque, core loss and copper loss of the permanent magnet synchronous motor change correspondingly with the fault degree. Finally, the harmonic amplitude analysis of the stators’ A phase current through the fast Fourier transform is carried out. It is found that the amplitude of the third harmonic (150 Hz) increases with the number of short circuits between the A phase stators, while other frequency harmonics amplitude is almost the same. The results can provide a basis for the diagnosis of this fault. At this stage, the study contribution is solely based on simulation analysis, we will try to test it by actual experiment later.

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