
Yan Wang, Jiaqiang Yang and Rongfeng Deng

College of Electrical Engineering, Zhejiang University, Hangzhou, 310027, China

This paper focus on the loss calculation for multiphase induction machine (IM) operating under fault-tolerant condition through filed-circuit coupling finite element method (FEM). Both one phase and two phases open-circuit faults of a 7-phase IM are researched and different spatial positions of the fault phases are taken into consideration. The magnitudes and phase angles of the residual phases current are deduced based on two constraint conditions, including equal magnitude of residual phases current and minimum stator copper loss. Then the time-stepping electromagnetic fields of the 7-phase IM under different faults conditions are calculated based on rotor field-oriented control (RFOC). The Joule loss and iron loss are calculated and the loss calculation results are useful for optimization design of fault-tolerant control strategy.

Index Terms—loss calculation, multiphase IM, fault-tolerant, field-circuit coupling FEM.

I. INTRODUCTION

The fault-tolerant capability of multiphase IM is an outstanding advantage for high-reliability application fields [1-2]. Fault-tolerant operating will cause the distortion of magnetic field and induce abundant harmonics components. It is necessary to investigate the loss of the multiphase IM operating under fault condition. The stator Joule loss can be obtained through the stator currents RMS. However, iron loss and rotor Joule loss is difficult to calculate due to the nonlinearity of iron core and the complex time-space harmonics [3]. The stator currents need to be closed loop controlled for fault condition due to the asymmetrical of electrical and magnetic structure, so field-circuit coupling FEM is used [4].

II. FAULT-TOLERANCE OPERATION STRATEGY

Both one phase and two phases open-circuit faults for a 7-phase IM are discussed in this section. The spatial positions of the fault phases are described in Fig.1. The 7-phase currents and magnetic motive force (MMF) can be expressed as (1) and (2).

\[ i_k = k_e \cos(\alpha t) \]

\[ \text{MMF} = \frac{7}{2} i_k e^{j\omega t} = i_1 + a i_2 + a^2 i_3 + a^3 i_4 + a^4 i_5 + a^5 i_6 + a^6 i_7 \]

where \( a = e^{j(2\pi/7)} = \cos(2\pi/7) + j \sin(2\pi/7) \).

In order to produce smooth torque for the multiphase IM under open-circuit fault condition, the stator MMF must be kept unchanged as health condition [1]. The constraints for the stator currents without neutral line can be given as

\[ \begin{align*}
 & i_1 \cos(0) + i_2 \cos(2\pi/7) + \cdots + i_7 \cos(12\pi/7) = 2/7 I_1 \\
 & i_1 \sin(0) + i_2 \sin(2\pi/7) + \cdots + i_7 \sin(12\pi/7) = 2/7 I_1 \\
 & i_1 + i_2 + \cdots + i_7 = 0
\end{align*} \]

Additional constraints are needed to solve the residual phase currents [2]. The constraints of minimum stator copper loss and equal current magnitude of residual phases can be given as

\[ f_{mm} = i_1^2 + i_2^2 + \cdots + i_7^2 \]

\[ k_1 = k_2 = \cdots = k_7 \]

The magnitudes and angles of the residual phase currents can be deduced based on (3)-(5) using lagrange multiplier method and the results which are per-unit are shown in Table I and II.

III. FEM CALCULATION RESULTS AND DISCUSSION

A. Field-circuit coupling FEM model

Due to the asymmetry of residual phase current under fault condition the method of supplying voltage source is infeasible, so the current closed-loop control is applied. The field-circuit coupling FEM model are shown in Fig.2, which is composed by 7-phase half-bridge inverter and 7-phase IM. The time and space harmonics caused by nonlinear inverter and circuit-open fault can be taken into consideration in this model. The fault-tolerant operation is carried out based on RFOC strategy using C program model. The rated frequency, voltage and torque of the prototype motor is 100Hz, 220V and 30Nm respectively.
The transient equation, field-circuit coupling equation, stator flux equation and mechanical equation are described as (6)-(9).
\[
\frac{\partial}{\partial x}(\mu \frac{\partial A}{\partial x}) + \frac{\partial}{\partial y}(\mu \frac{\partial A}{\partial y}) = -J + \sigma \frac{\partial A}{\partial t} \tag{6}
\]
\[
U_t = R \frac{dI_s}{dt} + L_s \frac{d\psi_s}{dt} \tag{7}
\]
\[
\psi_s = \frac{N}{S} \int \int A \, ds - \int \int A \, ds \tag{8}
\]
\[
J \frac{d\alpha}{dt} = T_e - T_L - D\omega_m \tag{9}
\]
where \( \mu, A, J, \sigma, \psi, L_s, N_s, I_s, J \) and \( \rho \) are magnetic permeability, \( z \) component of magnetic vector potential, stator current density, rotor bar conductivity, stator flux, stator end leakage inductance, area of stator winding, number of series turns, lamination length, moment of inertia and damping coefficient.

![Fig. 2. 7-phase IM field-circuit coupling FEM model.](image)

### B. Transient performance for field-circuit coupling FEM

The prototype is operated under the rated speed and the load torque decreases to 20N to ensure that the motor can keep stable under fault condition. The transient process of the stator phase currents, electromagnetic torque and rotor speed of the 7-phase IM from health condition to fault-tolerant condition are depicted in Fig. 3. Only case 1 and case 3 for constrain of equal magnitude of the residual phase currents are shown. The harmonic analysis of the air-gap flux density is drawn in Fig. 4.

![Fig. 3. Transient process of the 7-phase IM from health condition to open-circuit fault condition (10ms/div). (a)-(c) is for case 1 and (d)-(f) is for case 3; (a) and (b) 7-phase currents; (c) and (d) torque; (e) and (f) speed (rpm).](image)

![Fig. 4. Discrete Fourier decomposition of the air-gap flux density.](image)

### C. Loss calculation

The iron loss and Joule loss caused by the harmonic currents and harmonic magnetic fields are all included. Classic iron loss model is used in this paper, which can be given as (10) [5].
\[
P_I = P_{1} + P_{2} + P_{m} \tag{10}
\]
where \( P_1, P_2, P_m \) are the hysteresis loss, classic eddy-current loss and excess loss respectively.

The loss calculation results are shown in Table III and Table IV. The value is per-unit and the basic value is the loss under health condition. Due to the distortion of magnetic field and the increasing of harmonic components, both the iron loss and Joule loss are increased for the fault-tolerant condition comparing with health condition. The iron loss increases a little but the rotor Joule loss increase largely, because the harmonic magnetomotive force is produced by the interaction between the space harmonics of stator windings and the asymmetrical stator currents, which can induce harmonic currents in the rotor bars. The total loss is relatively small for the second constraints.

### IV. Conclusion

The iron loss, stator and rotor Joule loss are calculated, which can be used for optimal design of the fault-tolerant strategy for multiphase IM, simultaneously the loss calculation results can be used as heat sources for temperature analysis. The 7-phase IM experimental system is established to verify the proposed control strategy and loss calculation results based on efficiency.

### REFERENCES


