

Post-fault Operation for Five-phase Induction Machines under Single-Phase Open Using Symmetrical Components

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Abstract—This paper presents a current optimization technique based on symmetrical components theory for a five-phase full-pitch induction machine (IM) under an open circuit phase fault condition. A controller is proposed to maximize the magnitude of positive sequence component and minimize the magnitude of negative sequence component of the fundamental and the third harmonic currents based on symmetrical components. Further, other than the positive sequence current, magnitudes of the sequences are less than those of a conventional controller by using the genetic algorithm so as to reduce the couple degree between different harmonic subspaces. Its feasibility has been verified in experimental tests with a five-phase IM.

Keywords—five-phase IM; harmonic current injection; symmetrical components theory; fault tolerant control

I. INTRODUCTION

Multiphase machines have been used widely in electric ship propulsion, air-craft drives, locomotive traction, and high-power industrial applications [1]-[4]. As the number of phases increases, the required stator phase current amplitude can be reduced without changing phase voltages and output power [5]-[8]. Another distinguished advantage is that it can give additional degrees of freedom to fulfill high torque density and high power density using harmonic current injection [9]-[12].

Many papers have focused on the modeling and control algorithms for multiphase IMs under asymmetrical faults. The current command is required to produce a same rotating stator magnetomotive force (MMF) after one or more phases are open circuited [13]-[14]. A unified approach of modeling and field-oriented control of a dual three phase induction machine with one phase open is presented in [15]-[16]. A control scheme for fault-tolerant seven-phase IM drive based on multiple space vector representation is presented and the comparison of three different strategies is carried out by considering the first three spatial harmonics of the air-gap MMF [17]. However, all these methods lack comprehensive analysis for the couple degree between harmonic subspace [18], and the complexity for obtaining the optimum phase current increases as the number of machine phase increases [19].

In this paper, the couple degree for minimum peak current strategy is analysed based on symmetrical components theory and the current optimization technique proposed in [19] is extended considering harmonic current injection. A new objective function is proposed to achieve the same MMF, minimize the couple degree and improve iron utilization at the same time using genetic algorithm. Then the torque oscillation can be weakened compared with the conventional method in [20] and the computing process is simple. Finally, the five-phase concentrated full-pitch winding IM drive with low DC link is constructed and the feasibility of the proposed fault tolerant control (FTC) technique is verified by experiments.

II. FAULT-TOLERANT CONTROL BASED ON SYMMETRICAL CO-ORDINATE THEORY AND GENETIC ALGORITHM

An unbalanced multi-phase system can be represented as a combination of N symmetrical components [21]-[22] and the symmetrical component transformation for a five-phase current system is

$$\begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \\ S_5 \end{bmatrix} = \frac{1}{5} \begin{bmatrix} 1 & a & a^2 & a^3 & a^4 \\ 1 & a^2 & a^4 & a^6 & a^8 \\ 1 & a^3 & a^6 & a^9 & a^{12} \\ 1 & a^4 & a^8 & a^{12} & a^{16} \\ 1 & 1 & 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \\ i_d \\ i_e \end{bmatrix} \quad (1)$$

where S_1 is positive sequence 1 (A→B→C→D→E), S_4 is negative sequence 1 (A→E→D→C→B), S_3 is positive sequence 2 (A→D→B→E→C), S_2 is negative sequence 2 (A→C→E→B→D), I_{a5} is zero sequence (A→A→A→A→A), i_a, i_b, i_c, i_d, i_e are five phase currents, a is $e^{j\frac{2\pi}{5}}$, respectively.

In order to improve iron utilization and power density, the third harmonic current for each phase is integrated into the fundamental currents of the five-phase IM under the normal operations as [20].

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$$\begin{cases} i_a = i_{a1} + i_{a3} = I_1 \cos(\omega t) + I_3 \cos(3\omega t) \\ i_b = i_{b1} + i_{b3} = I_1 \cos(\omega t - \frac{2\pi}{5}) + I_3 \cos(3\omega t - \frac{6\pi}{5}) \\ i_c = i_{c1} + i_{c3} = I_1 \cos(\omega t - \frac{4\pi}{5}) + I_3 \cos(3\omega t - \frac{12\pi}{5}) \\ i_d = i_{d1} + i_{d3} = I_1 \cos(\omega t - \frac{6\pi}{5}) + I_3 \cos(3\omega t - \frac{18\pi}{5}) \\ i_e = i_{e1} + i_{e3} = I_1 \cos(\omega t - \frac{8\pi}{5}) + I_3 \cos(3\omega t - \frac{24\pi}{5}) \end{cases} \quad (2)$$

Where I_1 and I_3 are magnitudes of phase currents, i_{a1} , i_{b1} , i_{c1} , i_{d1} , i_{e1} and i_{a3} , i_{b3} , i_{c3} , i_{d3} , i_{e3} represent the five phase fundamental and third harmonic currents, ω is angle frequency, respectively. Using (1), the five symmetrical components using symmetrical transformation can be found in Table I and zero sequence components are equal to zero as a result of isolated neutral point.

TABLE I. SYMMETRICAL COMPONENTS FOR PRE-FAULT CURRENT

	S_1	S_2	S_3	S_4
Fundamental currents ($p.u$)	1	0	0	0
Third harmonic currents ($p.u$)	0	0	1	0

Under healthy conditions, only positive sequence 1 for fundamental currents and positive sequence 2 for third harmonic currents take the value of 1, respectively. With the aim of maintaining same stator MMF and achieving a maximum torque, the fault tolerant phase current command is [20].

$$\begin{cases} i_b^* = 1.382I_1 \cos(\omega t - \frac{\pi}{5}) + 3.618I_3 \cos(3\omega t - \frac{3\pi}{5}) \\ i_c^* = 1.382I_1 \cos(\omega t - \frac{4\pi}{5}) + 3.618I_3 \cos(3\omega t - \frac{2\pi}{5}) \\ i_d^* = 1.382I_1 \cos(\omega t + \frac{4\pi}{5}) + 3.618I_3 \cos(3\omega t + \frac{2\pi}{5}) \\ i_e^* = 1.382I_1 \cos(\omega t + \frac{\pi}{5}) + 3.618I_3 \cos(3\omega t + \frac{3\pi}{5}) \end{cases} \quad (3)$$

Symmetrical components distribution for conventional method is show in Table II. Compared with Table I, the second and the third sequence components can be defined as coupled sequence components since they are not equal to zero for fundamental current. Likewise, the first and the fourth sequence components are coupled sequence components for the third harmonic plane. These coupled components explain why there still exists torque pulsation under fault-tolerant control. It is worth noting that the magnitude of coupled sequence components for third harmonic currents is larger than 1 $p.u$, which will give rise to larger torque oscillations.

TABLE II. SYMMETRICAL COMPONENTS FOR CONVENTIONAL METHOD

	S_1	S_2	S_3	S_4
Fundamental currents ($p.u$)	1	-0.618	-0.382	0
Third harmonic currents ($p.u$)	1.618	0	1	-2.618

Hence this paper introduces a new current optimization technique based on genetic algorithm to reduce the couple degree. The control objective is to maximize the positive sequence components and minimize the negative sequence components provided that

- 1) Magnitude of all phase currents equal to 1 $p.u$.
- 2) Sum of all phase currents equals to zero.
- 3) Phase angles of stator phase currents are symmetrical around the real axis.
- 4) Third harmonic current injection.
- 5) Minimum couple degree.

The proposed objective function for the fundamental currents in the (phase a) open-circuit fault case is

$$\begin{cases} \min f_1 = \frac{|a^4 i_{b1} + a^3 i_{c1} + a^2 i_{d1} + a^1 i_{e1}|}{|a^1 i_{b1} + a^2 i_{c1} + a^3 i_{d1} + a^4 i_{e1}|} \\ \min f_2 = \frac{|a^2 i_{b1} + a^4 i_{c1} + a^6 i_{d1} + a^8 i_{e1}|}{|a^3 i_{b1} + a^6 i_{c1} + a^9 i_{d1} + a^{12} i_{e1}|} \\ i_{b1} + i_{c1} + i_{d1} + i_{e1} = 0 \end{cases} \quad (4)$$

After obtaining the optimum solution, the currents are multiplied by a constant factor in order to let the magnitude of positive sequence 1 be equal to 1 $p.u$ [19]. Similarly, the objective function for third harmonic currents is

$$\begin{cases} \min f_1 = \frac{|a^2 i_{b3} + a^4 i_{c3} + a^6 i_{d3} + a^8 i_{e3}|}{|a^3 i_{b3} + a^6 i_{c3} + a^9 i_{d3} + a^{12} i_{e3}|} \\ \min f_2 = \frac{|a^1 i_{b3} + a^2 i_{c3} + a^3 i_{d3} + a^4 i_{e3}|}{|a^4 i_{b3} + a^3 i_{c3} + a^2 i_{d3} + a^1 i_{e3}|} \\ i_{b3} + i_{c3} + i_{d3} + i_{e3} = 0 \end{cases} \quad (5)$$

Then the optimum currents in the remaining phases are shown in (6) and symmetrical components for optimum currents are presented in Table III.

TABLE III. SYMMETRICAL COMPONENTS FOR PROPOSED METHOD

	S_1	S_2	S_3	S_4
Fundamental currents ($p.u$)	1	-0.618	-0.382	0
Third harmonic currents ($p.u$)	-0.618	0	1	-0.382

$$\begin{cases} i_b = 1.382I_1 \cos(\omega t - \frac{\pi}{5}) + 1.382I_3 \cos(3\omega t + \frac{4\pi}{5}) \\ i_c = 1.382I_1 \cos(\omega t - \frac{4\pi}{5}) + 1.382I_3 \cos(3\omega t - \frac{\pi}{5}) \\ i_d = 1.382I_1 \cos(\omega t + \frac{4\pi}{5}) + 1.382I_3 \cos(3\omega t + \frac{\pi}{5}) \\ i_e = 1.382I_1 \cos(\omega t + \frac{\pi}{5}) + 1.382I_3 \cos(3\omega t - \frac{4\pi}{5}) \end{cases} \quad (6)$$

Sequence components for fundamental current are same with the conventional method, however, the magnitude of positive sequence 1 and negative 1 for third harmonic current decrease by 61.8% and 85.4% after optimization, which exerts a positive effect on torque ripple suppression.

In order to generate a rectangular flux distribution in the air-gap based on rotor field oriented control under both the health and fault conditions [23], the relationships between the quadrature and direct currents in both planes and the slip frequency are

$$i_{qs3} = \frac{1}{6} \frac{L_{m1}}{L_{m3}} \frac{L_{r3}}{L_{r1}} \frac{r_1}{r_3} i_{qs1} \quad (7)$$

$$i_{ds3} = \frac{1}{18} \frac{L_{m1}}{L_{m3}} i_{ds1} \quad (8)$$

$$\omega_{s1} = \frac{i_{qs1} r_1}{i_{ds1} L_{r1}} \quad (9)$$

where i_{qs1} , i_{ds1} , i_{qs3} , i_{ds3} , L_{r1} , L_{r3} , L_{m1} , L_{m3} , r_1 , r_3 are the quadrature currents, direct currents, rotor inductances, magnetizing inductances and rotor resistances in the fundamental and the third harmonic plane, respectively. The proposed current commands in rotor field oriented control mode are as (10).

Besides, a proportional resonant regulator is adopted to realize excellent current tracking performance in the phase frame [18]. The overall schematic diagram is shown in Fig. 1.

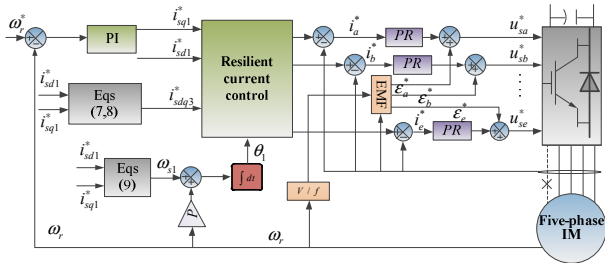


Fig. 1. Block diagram of fault tolerant control for five-phase IM under single phase open.

$$\begin{cases} i_a^* = 0 \\ i_b^* = 1.382(i_{ds1}^* \cos(\theta - \frac{\pi}{5}) + i_{qs1}^* \sin(\theta - \frac{\pi}{5})) \\ \quad + 1.382(i_{ds3}^* \cos(3\theta + \frac{4\pi}{5}) + i_{qs3}^* \sin(3\theta + \frac{4\pi}{5})) \\ i_c^* = 1.382(i_{ds1}^* \cos(\theta - \frac{4\pi}{5}) + i_{qs1}^* \sin(\theta - \frac{4\pi}{5})) \\ \quad + 1.382(i_{ds3}^* \cos(3\theta - \frac{\pi}{5}) + i_{qs3}^* \sin(3\theta - \frac{\pi}{5})) \\ i_d^* = 1.382(i_{ds1}^* \cos(\theta + \frac{4\pi}{5}) + i_{qs1}^* \sin(\theta + \frac{4\pi}{5})) \\ \quad + 1.382(i_{ds3}^* \cos(3\theta + \frac{\pi}{5}) + i_{qs3}^* \sin(3\theta + \frac{\pi}{5})) \\ i_e^* = 1.382(i_{ds1}^* \cos(\theta + \frac{\pi}{5}) + i_{qs1}^* \sin(\theta + \frac{\pi}{5})) \\ \quad + 1.382(i_{ds3}^* \cos(3\theta + \frac{4\pi}{5}) + i_{qs3}^* \sin(3\theta + \frac{4\pi}{5})) \end{cases} \quad (10)$$

III. EXPERIMENTAL RESULTS AND DISCUSSION

To compare the performance between the conventional method and proposed method, a five-phase multiphase IM with concentric windings is adopted in experiment.

The basic configuration of the experimental system is presented in Fig. 2. It consists of a five-phase IM interfaced with a digital control board based on a TMS320F28335 for control and optimum algorithm implementation. Coupled with a Vortex loader, the IM is driven by a multiphase voltage-source inverter, which operates at 8 kHz switching frequency and uses SPWM with a rated DC link voltage of 72 V.

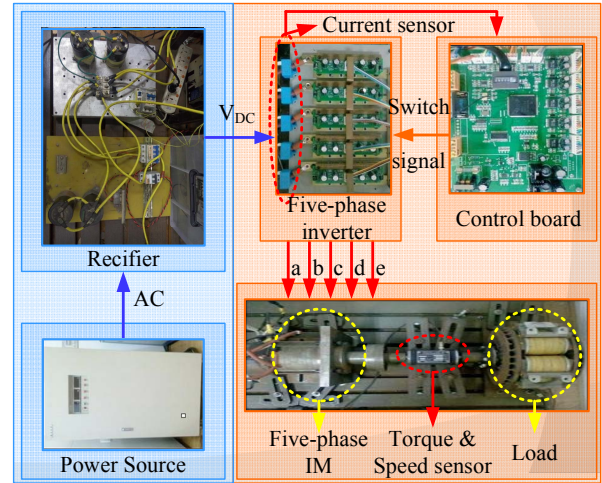


Fig. 2. Experimental platform of control system

The stator windings of the five-phase IM are evenly distributed with spatial angles of 72° . The rated parameters are demonstrated in Table IV and the structural parameters are presented in Table V.

TABLE IV. RATED PARAMETERS OF THE FIVE-PHASE IM

Parameter	Value	Parameter	Value
Rated power (kW)	5.0	Rated torque (N·m)	25.0
Rated voltage (V)	19	R_s (mΩ)	11.0
Rated current (A)	73.0	R_{r1} (mΩ)	8.1
Number of poles	4	R_{r3} (mΩ)	7.8
Rated speed (rpm)	1940	L_{m1} (mH)	1.63
Rated frequency (Hz)	66.7	L_{m3} (mH)	0.19

TABLE V. STRUCTURAL PARAMETERS OF THE FIVE-PHASE IM

Parameter	Value
Outer diameter (mm)	165
Inner diameter (mm)	104
Air-gap length (mm)	0.4
Yoke length (mm)	14
Stator slots	40
Teeth width(mm)	4.28

The conventional algorithm and the proposed algorithm are tested in a 12 N·m mechanical load and the reference speed is 300 r/min. To evaluate the performance of proposed method under single-phase open condition, two indicators are considered including torque ripple and stator losses. According to [21], the copper loss in stator is expressed as

$$P_{cu} = |I_{a1}|^2 + |I_{a2}|^2 + |I_{a3}|^2 + |I_{a4}|^2 \quad (11)$$

The experimental results in Fig. 3 illustrate the five stator currents for the conventional controller and the proposed controller. The copper loss of conventional method is 1.528 p.u for fundamental currents and 10.472 p.u for third harmonic currents. However, for the proposed method, the copper loss for both kinds of current are 1.528 p.u.

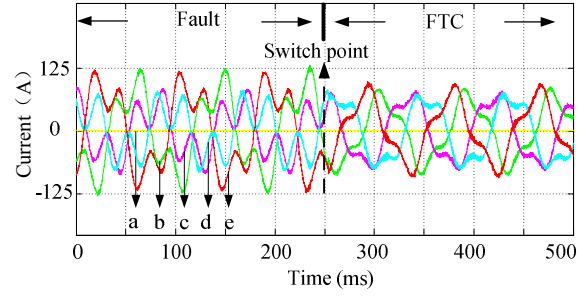
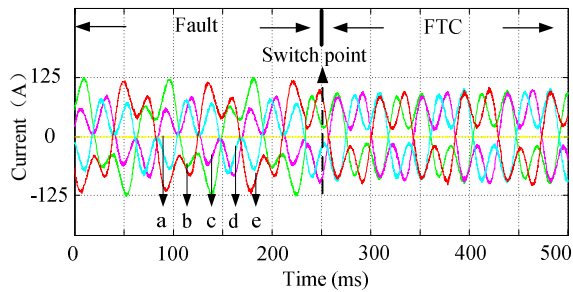


Fig. 3. Five-phase stator current: (a) conventional controller; (b) proposed controller

Torque ripple is a key value for drive system and it is defined as [18].

$$\Delta T_e = \frac{T_{e\max} - T_{e\min}}{T_{e\text{avg}}} \quad (12)$$

In Fig. 4, the torque ripple is 12.10% and 40.35% in healthy conditions and post-fault operation with the conventional controller, respectively. While with the proposed controller, the torque ripple is reduced to 17.75%, which validates the control goal.

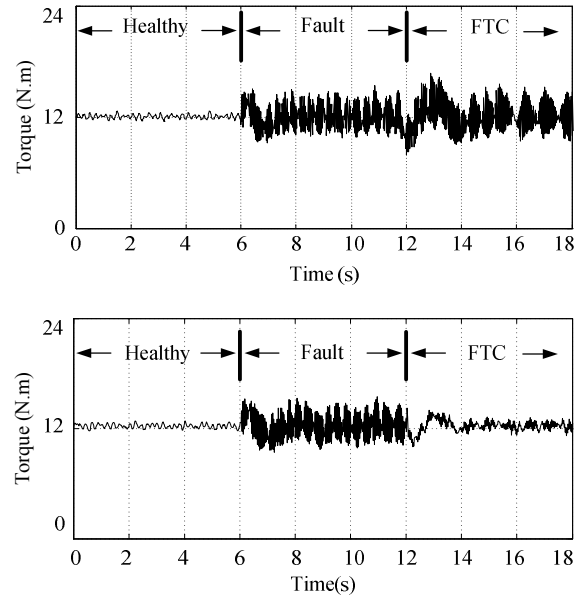


Fig. 4. Electromagnetic torque: (a) conventional controller; (b) proposed controller

IV. CONCLUSIONS

This paper optimizes phase currents for a five-phase IM under single phase open fault condition based on symmetrical components method and the genetic algorithm. The couple degree of the conventional controller with harmonic current injection is investigated and a new controller is proposed to reduce the amplitude of couple sequence components. The

magnitude of positive sequence component is maximized and the magnitude of negative sequence component is minimized at the same time so as to maintain the same stator MMF. Compared with conventional method, magnitudes of coupled sequence components for third harmonic currents are reduced significantly. It is shown that the torque ripple and copper loss are smaller than the conventional method.

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