Remedial Phase-Angle Control of a Five-Phase Fault-Tolerant Permanent-Magnet Vernier Machine With Short-Circuit Fault

Wenxiang Zhao, Chenyu Gu, Qian Chen, Jinghua Ji, and Dezhi Xu

(Invited)

***Abstract*—A fault-tolerant permanent-magnet vernier (FT-PMV) machine incorporates the merits of high fault-tolerant capability and high torque density. In this paper, a remedial phase-angle control (RPAC) strategy is proposed for a five-phase FT-PMV machine with short-circuit fault. Firstly, the proposed strategy can reduce the amount of unknown quantities by structuring the phase-angles of the normal phases. It can simplify the calculation of the remedial currents. Then, in order to obtain the desired torque, only the amplitudes of the remedial currents need to be calculated. Based on the principle of instantaneous electrical input power and mechanical output power balance condition, the real components are used to maintain the torque capability, while the reactive components are limited zero to minimize the torque ripple. Both simulations and experiments are presented to verify the proposed RPAC strategy.**

***Index Terms*—Fault-tolerant permanent-magnet vernier (FT-PMV) machine, remedial phase-angle control (RPAC), short-circuit fault.**

I. INTRODUCTION

ELECTRICAL drive is the core equipment of many important engineering applications such as the aerospace, military equipment and transportation [1]-[3]. High fault-tolerance is a desirable feature for a machine drive, by which the system can keep the predicted performances even partial fault happened. A variety of fault-tolerant machines have been reported [4]-[8]. Among these existing fault-tolerant machines, the five-phase fault-tolerant permanent-magnet (PM) vernier (FT-PMV) machine incorporates the merits of high fault-tolerant capability and high torque density.

On the other hand, a variety of fault-tolerant control strategies have been investigated. The fault-tolerant operations of conventional three-phase machines with open-circuit fault have been proposed [9]-[12]. Compared to traditional three-phase machines, the multiphase machines have higher fault tolerant capability. When faults occur in one or more phases, the multiphase machine can maintain torque performance without additional hardware [13]-[14]. Thus, lots of fault-tolerant control strategies have been proposed for these multiphase machines. In [15], the fault-tolerant control strategies for a five-phase PM machine with different open-circuit faults were presented. The remedial strategies for a five-phase PM machine considering different connections of stator windings were proposed in [16]. These methods also reduced ohmic loss and torque ripple. The proposed fault-tolerant control methods in [17] considered the third-harmonic current components for the excitation of normal phases. Besides, remedial control strategies based on CFPWM, the remedial control strategies based on SVPWM have been investigated [18].

Although many literatures have reported optimal fault-tolerant control strategies, most of them focus on open-circuit fault, rather than short-circuit fault. In [19], a fault-tolerant operation of a five-phase PM machine with short-circuit fault was investigated. However, the torque ripple is significant, and the remedial currents are not optimized. The global closed-form solutions for optimal currents under short-circuit fault condition were proposed in [20]. In [21]-[24], the fault-tolerant operation has been extended to the controller fault.

In this paper, a remedial phase-angle control (RPAC) strategy will be proposed for a five-phase FT-PMV machine with short-circuit fault. Firstly, the calculation can be simplified by ingenious phase-angle structure. During the structuring, the currents in normal phases can produce the same reactive components as the faulty one. Then, only the amplitudes of remedial currents need calculation to maintain the desired torque.

This paper is organized as follows. Exhaustive derivation of the proposed RPAC strategy is described in Section II. The RPAC strategy is based on the theory of instantaneous balance between electrical input and mechanical output. The simulated results about characteristics of the used machine and operating status in normal, short-circuit and fault-tolerant conditions are discussed in Section III. The experimental results are presented

This work was supported by the National Natural Science Foundation of China (51422702), by the by the Qing Lan Project, and by the Priority Academic Program Development of Jiangsu Higher Education Institutions.

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to verify the proposed RPAC strategy in Section IV. Finally, Section V concludes this work.

II. PROPOSED CONTROL STRATEGY

The RPAC strategy for a five-phase FT-PMV machine with short-circuit fault will be derived in this section. Fig.1 shows a steady-state post-fault schematic of short-circuit fault. It is assumed that the short-circuit fault occurs at the terminals of the stator wingdings in phase-a. Then, its short-circuit current can be written as

$$i_a' = I_f \cos(\omega t - \theta) \tag{1}$$

where I_f is the amplitude of the short-circuit current, and θ is the angle between the short-circuit current and the no-load back-EMF in the faulty phase.

The back-EMFs of a five-phase FT-PMV machine can be described as

$$\begin{cases} e_a = E\cos(\omega t) \\ e_b = E\cos(\omega t - \frac{2\pi}{5}) \\ e_c = E\cos(\omega t - \frac{4\pi}{5}) \\ e_d = E\cos(\omega t + \frac{4\pi}{5}) \\ e_e = E\cos(\omega t + \frac{2\pi}{5}) \end{cases} \tag{2}$$

The instantaneous power of phase-a can be expressed as

$$\begin{cases} e_a i_a' = p + q \\ p = \frac{1}{2} E I_f \cos\theta \\ q = \frac{1}{2} E I_f \cos(2\omega t - \theta) \end{cases} \tag{3}$$

From (3), it can be found that the instantaneous power of phase-a is consistent with two components. One is the real component (p) produced by constant torque, while the other is the reactive component (q) produced by pulsating torque. The phase-angles of heathy phases can be given directly, rather than the complex calculation to reduce the amount of unknown quantities. This can significantly simplify the calculation of the remedial currents. Due to the structured phase-angles, every healthy phase generates a reactive component similar to the faulty one. Then, the currents of these healthy phases can be expressed as

$$\begin{cases} i_b' = x_1 I_f \cos(\omega t - \theta + \frac{2}{5}\pi) \\ i_c' = x_2 I_f \cos(\omega t - \theta + \frac{4}{5}\pi) \\ i_d' = x_3 I_f \cos(\omega t - \theta - \frac{4}{5}\pi) \\ i_e' = x_4 I_f \cos(\omega t - \theta - \frac{2}{5}\pi) \end{cases} \tag{4}$$

By applying the instantaneous electrical input power and mechanical output power balance condition, it can be obtained

$$\begin{aligned} T\omega &= e_a i_a' + e_b i_b' + e_c i_c' + e_d i_d' + e_e i_e' \\ &= \frac{1}{2} E I_f \{[\cos(\theta) + x_1 \cos(\theta - \frac{4}{5}\pi) \\ &\quad + x_2 \cos(\theta - \frac{8}{5}\pi) + x_3 \cos(\theta + \frac{8}{5}\pi) \\ &\quad + x_4 \cos(\theta + \frac{4}{5}\pi)] \\ &\quad + [\cos(2\omega t - \theta) + x_1 \cos(2\omega t - \theta) \\ &\quad + x_2 \cos(2\omega t - \theta) + x_3 \cos(2\omega t - \theta) \\ &\quad + x_4 \cos(2\omega t - \theta)]\} \end{aligned} \tag{5}$$

Under the normal condition, it can be obtained

$$\begin{aligned} T\omega &= e_a i_a + e_b i_b + e_c i_c + e_d i_d + e_e i_e \\ &= \frac{5}{2} E I \end{aligned} \tag{6}$$

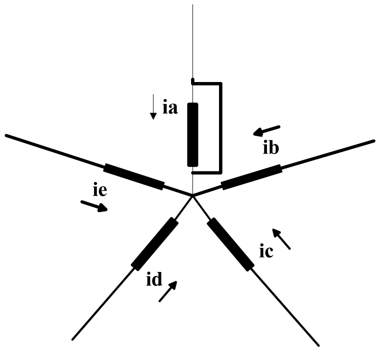


Fig.1. Short-circuit fault at the terminals of stator windings in phase-a.

To maintain torque capability, the sum of the real components ($\sum p$) should produce the required torque. Moreover, to obtain ripple free torque, the sum of the reactive components ($\sum q$) should be constrained to zero. Therefore, the remedial currents should satisfy the constraints as follows

$$\begin{cases} \frac{5}{2} E I = \frac{1}{2} E I_f [\cos(\theta) + x_1 \cos(\theta - \frac{4}{5}\pi) \\ \quad + x_2 \cos(\theta - \frac{8}{5}\pi) + x_3 \cos(\theta + \frac{8}{5}\pi) \\ \quad + x_4 \cos(\theta + \frac{4}{5}\pi)] \\ 0 = \frac{1}{2} E I_f [\cos(2\omega t - \theta) + x_1 \cos(2\omega t - \theta) \\ \quad + x_2 \cos(2\omega t - \theta) + x_3 \cos(2\omega t - \theta) \\ \quad + x_4 \cos(2\omega t - \theta)] \end{cases} \tag{7}$$

Then, it can be simplified as

$$\begin{cases} 5I = I_f [\cos(\theta) + x_1 \cos(\theta - \frac{4}{5}\pi) \\ \quad + x_2 \cos(\theta - \frac{8}{5}\pi) + x_3 \cos(\theta + \frac{8}{5}\pi) \\ \quad + x_4 \cos(\theta + \frac{4}{5}\pi)] \\ 0 = x_1 + x_2 + x_3 + x_4 + 1 \end{cases} \tag{8}$$

In the normal condition, I=2. Furthermore, the sum of currents in the normal phases should be constraint at zero.

$$i_b' + i_c' + i_d' + i_e' = 0 \tag{9}$$

Also, it can be expressed as

$$\begin{cases} 0 = x_1 \cos\frac{2}{5}\pi + x_2 \cos\frac{4}{5}\pi \\ \quad + x_3 \cos\frac{4}{5}\pi + x_4 \cos\frac{2}{5}\pi \\ 0 = -x_1 \sin\frac{2}{5}\pi - x_2 \sin\frac{4}{5}\pi \\ \quad + x_3 \sin\frac{4}{5}\pi + x_4 \sin\frac{2}{5}\pi \end{cases} \tag{10}$$

Fig. 4 depicts the short-circuit current and the normal back-EMF of the faulty phase when the FT-PMV machine operates at 200 rpm. Based on the back-EMF and the short-circuit current, If and θ in (1) can be obtained as follows

$$\begin{cases} I_f = 7.95A \\ \theta = 1.402\pi \end{cases} \tag{11}$$

According to (8), (10) and (11), it can be calculated as follows

$$\begin{cases} x_1 = \text{-}0.7824 \\ x_2 = 0.5421 \\ x_3 = \text{-}0.8185 \\ x_4 = 0.0588 \end{cases} \tag{12}$$

Thus, the remedial currents of the normal phases can be obtained as

$$\begin{cases} i'_b = -0.7824 I_f \cos(\omega t - 1.402\pi + \frac{2}{5}\pi) \\ i'_c = 0.5421 I_f \cos(\omega t - 1.402\pi + \frac{4}{5}\pi) \\ i'_d = -0.8185 I_f \cos(\omega t - 1.402\pi - \frac{4}{5}\pi) \\ i'_e = 0.0588 I_f \cos(\omega t - 1.402\pi - \frac{2}{5}\pi) \end{cases} \tag{13}$$

III. SIMULATION

To examine the proposed RPAC strategy, a five-phase FT-PMV machine [4] is used for verification in this paper. Its cross section is displayed in Fig. 2. The number of stator slots is 20 and the rotor has 31 pole pairs. The machine has each coil wound around a single tooth, which is the so-called single-layer fractional-slot concentrated windings.

Moreover, the FEA-based predicted back-EMFs of the five-phase FT-PMV machine are shown in Fig. 3. Fig. 4 depicts the short-circuit current and the normal Back-EMF of the faulty phase when the FT-PMV machine operates at 200 rpm. It is obvious that the short-circuit current is limited well because of the appropriate fault-tolerant design.

Under the normal condition, the FT-PMV machine is excited with balanced five-phase sinusoidal currents due to its sinusoidal back-EMFs. Fig. 5 shows the current and torque waveforms of the five-phase FT-PMV machine under the normal condition, illustrating a torque ripple of 25.0%. The current and torque waveforms of the five-phase FT-PMV machine under the short-circuit fault condition are shown in Fig.6. The torque ripple of 233.3% can be seen with short-circuit fault in single phase. By using the proposed RPAC strategy, not only the average torque can be maintained, but also the torque ripple can be minimized. Fig. 7 shows the improved performances of machine drive when the five-phase FT-PMV machine is with the fault condition of short-circuit. It can be seen that the torque ripple value is 36.8%. Obviously, the proposed RPAC strategy is effective to minimize the torque ripple caused by the short-circuit fault. Hence, the proposed RPAC strategy can enhance the performance of the faulty operation, slightly inferior to that of the normal operation.

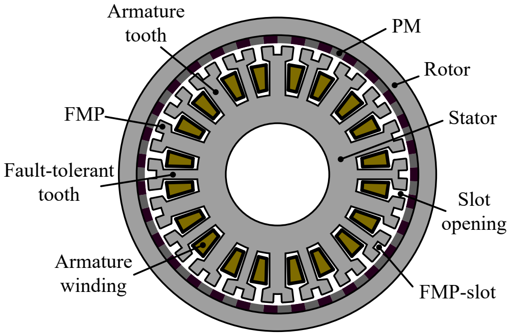


Fig. 2. Cross section of FT-PMV machine.

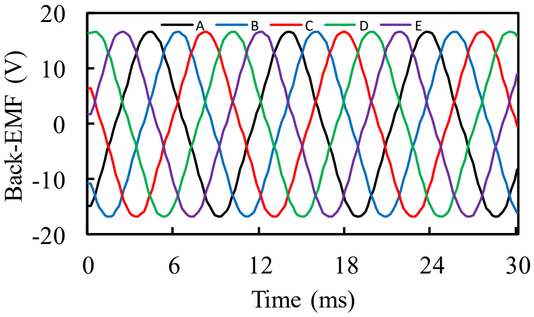


Fig. 3. Back-EMF waveforms.

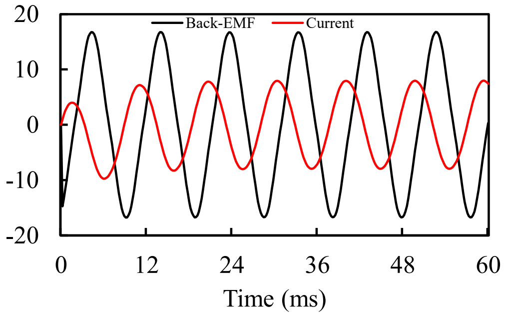
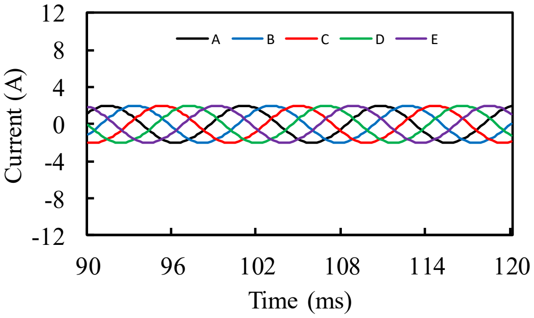
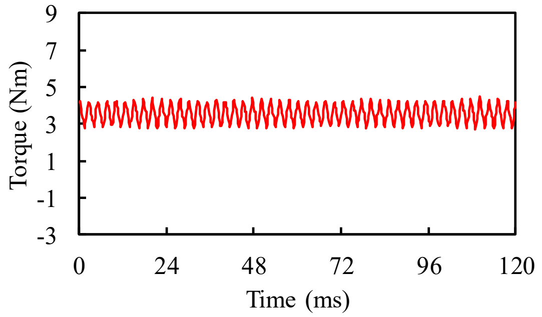


Fig. 4. Back-EMF and short-circuit current.

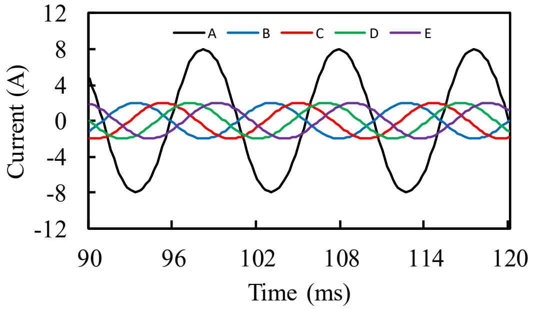


(a) Currents

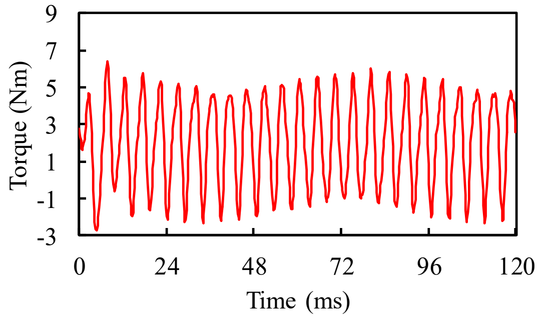


(b) Torque

Fig. 5 Waveforms in normal operation.

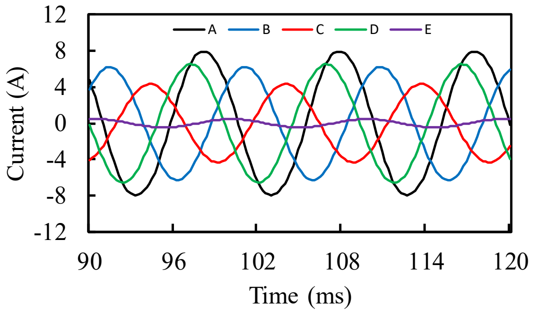


(a) Currents

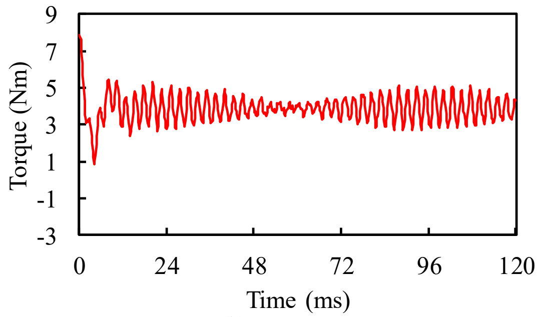


(b) Torque

Fig. 6 Waveforms in faulty operation.



(a) Currents



(b) Torque

Fig.7. Waveforms in fault-tolerant operation.

IV. EXPERIMENTAL VERIFICATION

In order to validate the effectiveness of the theoretical analysis, a five-phase FT-PMV machine is designed and built. For this experiment, an IPM-based converter and a DSP-based digital controller are implemented to drive the machine. A separately excited dc generator is used as the variable load. To measure the torque of the proposed machine drive, a transient torque transducer is mounted between the five-phase FT-PMV machine and the dc generator. Moreover, the currents are sensed by the Hall-effect sensors and the position signal is obtained by the optical encoder with an accuracy of 2048 counts per revolution. The test bench of the five-phase FT-PMV machine is shown in Fig. 8.

The block diagram of the control scheme is illustrated in Fig. 9, in which ω_{ref} is the reference speed and ξ is the position angle feedback from the machine. The currents i^*_{a}, i^*_{b}, i^*_{c}, i^*_{d} and i^*_{e} of the short-circuit fault-tolerant control strategy are calculated by using the module of RPAC. The signals in the gate driver for a five-phase inverter come from a hysteresis current controller.

The experimental results under the normal condition are shown in Fig. 10. The torque ripple is relatively small and the currents are sinusoidal. Fig. 11 shows the short-circuit current of the faulty phase and the back-EMFs of other healthy phases. Based on the short-circuit current of faulty phase and back-EMF of adjacent formal phase, If and θ in (1) that required during calculation of remedial currents can be obtained. At the same time, it can be seen that the short-circuit current of the faulty phase has insignificant effect on the back-EMFs of the normal phase and the experiment result can validate the independence between phases. Fig. 12 shows the torque currents under the short-circuit fault condition. It can be seen that the torque ripple becomes a little larger and the currents in normal phases have serious distortion. The machine can still be working due to the fault-tolerant feature of the machine and close-loop control system. The experimental results in the fault-tolerant operation are shown in Fig. 13. It can be seen that the torque capability is maintained and the torque ripple is minimized. The relationship between remedial currents is in good agreement with the proposed analysis and simulations. At the same time, the currents of normal phases are sinusoidal.

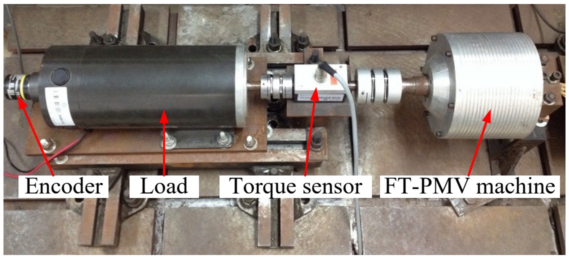


Fig. 8. Test bench of Five-phase FT-PMV machine.

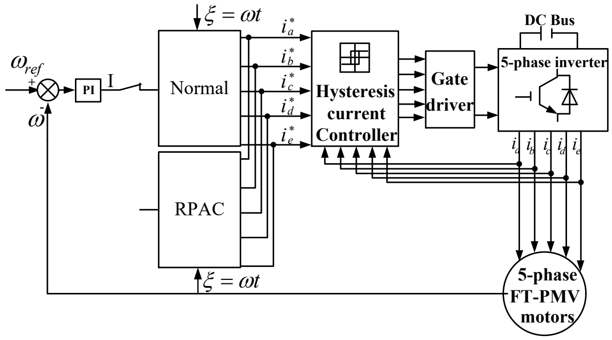


Fig. 9. Block diagram of control scheme.

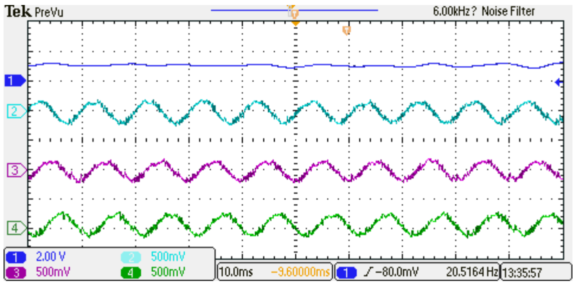


Fig. 10 Measured torque (trace 1) and currents of pahse a-c (trace 2-4) at normal operation (10ms/div, 4Nm/div, 5A/div).

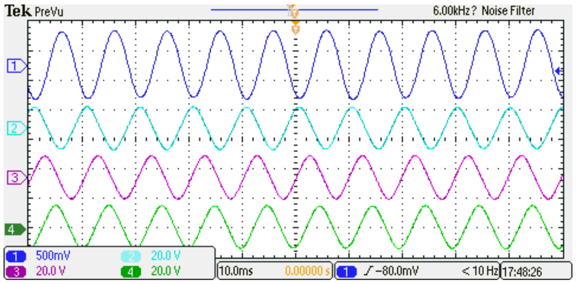


Fig. 11. Measured short-circuit phase current (trace 1) and its adjacent phase back-EMFs of pahse b-d (traces 2-4) (10ms/div, 5A/div, 20V/div).

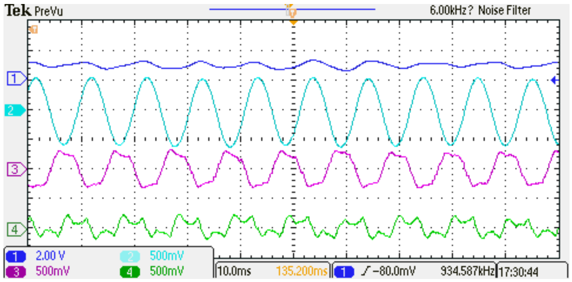


Fig. 12. Measured torque (trace 1) and currents of phase a-c (trace 2-4) in short-circuit operation (10ms/div, 4Nm/div, 5A/div)

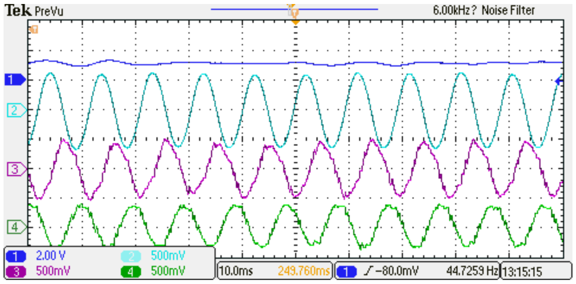


Fig. 13. Measured torque (trace 1) and currents of phase a-c (trace 2-4) at fault-tolerant operation (10ms/div, 4Nm/div, 5A/div).

V. CONCLUSION

In this paper, a RPAC strategy for a five-phase FT-PMV machine with short-circuit fault has been proposed. The amount of the unknown quantities can be saved by structuring the phase-angles of the healthy phases directly. Compared to the existing strategies, the calculation of remedial currents can be simplified greatly. Then, the amplitudes of remedial currents have been calculated to maintain required torque and minimize torque ripple. A five-phase FT-PMV machine has been used to verify the proposed strategy. The simulations and experiments are both in agreement with the proposed analysis. It shows that the proposed RPAC strategy can maintain torque performance and minimize torque ripple during the short-circuit fault. Hence, it has a bright future in high-reliability and high fault-tolerant applications.

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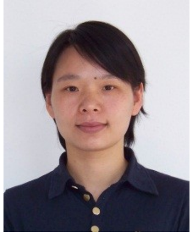

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