Fault-Tolerant Analysis and Design of AFPMSM With Multi-Disc Type Coreless Open-End Winding

Xiaoguang Wang
Meng Zhao
Lei Tang
Wei Xu
weix@uow.edu.au

Md Rabiul Islam
University of Wollongong, mrislam@uow.edu.au

Follow this and additional works at: https://ro.uow.edu.au/eispapers1

Part of the Engineering Commons, and the Science and Technology Studies Commons

Recommended Citation
Wang, Xiaoguang; Zhao, Meng; Tang, Lei; Xu, Wei; and Islam, Md Rabiul, "Fault-Tolerant Analysis and Design of AFPMSM With Multi-Disc Type Coreless Open-End Winding" (2020). Faculty of Engineering and Information Sciences - Papers: Part B. 4381.
https://ro.uow.edu.au/eispapers1/4381

Research Online is the open access institutional repository for the University of Wollongong. For further information contact the UOW Library: research-pubs@uow.edu.au
Fault-Tolerant Analysis and Design of AFPMSM With Multi-Disc Type Coreless Open-End Winding

Abstract
This article presents a multi-disc coreless axial flux permanent magnet synchronous machine (MDC-AFPMSM) with N pole and S pole type series magnetic circuit and open-end winding for high reliability applications, such as small power actuator system. Firstly, the topology and driving modes of MDC-AFPMSM are presented in details. In this article, a multi-objective optimization function is proposed to design the machine with full consideration of various influence factors. The drive performance indexes of four-phase, five-phase and six-phase machines are analyzed and discussed. Furthermore, main parameters of the five-phase MDC-AFPMSM with open-end winding are calculated. In order to reduce the torque ripple, the air gap magnetic flux is optimized. Finally, the operation characteristics under short-circuit and open-circuit faults are fully analyzed based on the three-dimensional (3D) finite element algorithm. Comprehensive simulation results and theoretical analysis have demonstrated that the open-end winding MDC-AFPMSM has much stronger fault-tolerant ability in comparison to that of conventional machines.

Keywords
fault-tolerant, analysis, design, multi-disc, winding, afpmsm, open-end, coreless, type

Disciplines
Engineering | Science and Technology Studies

Publication Details
X. Wang, M. Zhao, L. Tang, W. Xu & M. Islam, "Fault-Tolerant Analysis and Design of AFPMSM With Multi-Disc Type Coreless Open-End Winding," IEEE Access, vol. 8, pp. 171744-171753, 2020.

This journal article is available at Research Online: https://ro.uow.edu.au/eispapers1/4381
Fault-Tolerant Analysis and Design of AFPMSM With Multi-Disc Type Coreless Open-End Winding

XIAOGUANG WANG, MENG ZHAO, LEI TANG, WEI XU, (Senior Member, IEEE), AND MD. RABIUL ISLAM, (Senior Member, IEEE)

1Hubei Key Laboratory for High-Efficiency Utilization of Solar Energy and Operation Control of Energy Storage System, Hubei University of Technology, Wuhan 430068, China
2School of Electrical Engineering, Southwest Jiaotong University, Chengdu 611756, China
3State Key Laboratory of Advanced Electromagnetic Engineering and Technology, School of Electrical and Electronic Engineering, Huazhong University of Science and Technology, Wuhan 430074, China
4School of Electrical, Computer and Telecommunications Engineering, University of Wollongong, Wollongong, NSW 2522, Australia

Corresponding author: Lei Tang (leitangsai@foxmail.com)

This work was supported in part by the Natural Science Foundation of Hubei Province under Grant 2019CFB759, the Key Technical Innovation Program of Hubei Province under Grant 2019AAA026, the National Natural Science Foundation of China under Grants 51877093, and the National Key Research and Development Program of China under Grant 2018YFE0100200.

ABSTRACT

This article presents a multi-disc coreless axial flux permanent magnet synchronous machine (MDC-AFPMSM) with N pole and S pole type series magnetic circuit and open-end winding for high reliability applications, such as small power actuator system. Firstly, the topology and driving modes of MDC-AFPMSM are presented in details. In this article, a multi-objective optimization function is proposed to design the machine with full consideration of various influence factors. The drive performance indexes of four-phase, five-phase and six-phase machines are analyzed and discussed. Furthermore, main parameters of the five-phase MDC-AFPMSM with open-end winding are calculated. In order to reduce the torque ripple, the air gap magnetic flux is optimized. Finally, the operation characteristics under short-circuit and open-circuit faults are fully analyzed based on the three-dimensional (3D) finite element algorithm. Comprehensive simulation results and theoretical analysis have demonstrated that the open-end winding MDC-AFPMSM has much stronger fault-tolerant ability in comparison to that of conventional machines.

INDEX TERMS

Axial flux permanent magnet synchronous machine, coreless, fault-tolerance, multi-objective optimization, open-end winding.

I. INTRODUCTION

Electric actuator replaced traditional hydraulic mechanism in the intelligent equipment and its use has been considerably increased during the last decades. The intelligent electric actuator of the power plant has enhanced reliability, which ensures the rational working [1]. Similarly, the electric actuator used in ships needs high reliability [2]. Therefore, achieving the machine in the actuator with higher reliability, fault-tolerant and enhanced actuating qualities when the actuator performs corresponding actions at critical moments has become one of the main objectives. The fault-tolerant machine can still maintain the required performance due to high degree of control freedom when the machine system breaks down. In addition, it also has the ability of fault isolation and suppression. Consequently, fault-tolerant machines have attracted more attention from experts coming from the fields of aviation, aerospace, electric vehicles, and so on [3].

Although traditional fault-tolerant machines with iron core are popular in the industrial systems, they have some problems, such as cogging torque, magnetic field saturation, nonlinear parameters, poor overload capacity, and poor drive performance under fault operation. Therefore, improving fault tolerance capability is one of the main targets by the designers. The coreless axial flux permanent magnet synchronous machine (AFPMSM) has the characteristics of low cogging torque ripple, low magnetic circuit saturation effect, almost linear parameters, high peak torque, better overload capacity and fast current response speed compared with those of the traditional iron core fault-tolerant machines. Furthermore, the multi-disc AFPMSM with fault tolerance has better electromagnetic thermal physical isolation ability, which can get superior fault tolerance ability during fault...
working states. According to the requirements of actuator applications, multi-disc AFPMSM has significant overload capacity, which can ensure that the machine can also provide the necessary torque output in a short time after failure [3]. Therefore, the small power fault-tolerant AFPMSM would unleash the potentiality of such machines in actuator.

Till now, fault-tolerant machines have one of the popular topics in the field of electrical machines. In [3], authors summarized main features of the fault-tolerant machines as follows: (1) surface mounted structure, (2) large phase inductance, (3) concentrated winding, and (4) only one phase winding in each slot. In [4], electromagnetic performances of the permanent magnet brushless machine with pitch winding and full tooth winding were fully compared in this article. The results showed that pitch winding machines were more suitable for fault-tolerant operation because of its large self-inductance and small mutual inductance. A five-phase fault-tolerant machine (20 slots and 18 poles) can get higher self-inductance, zero mutual inductance, which can suppress some short-circuit current effectively [5].

The fault-tolerant machine has the characteristics of electrical isolation, physical isolation, thermal isolation, magnetic isolation, and short-circuit current suppression [6]. In [7], authors presented one machine, in which each phase winding is excited by H-bridge power supply, separately. Hence, this topology can get the electrical isolation between different windings effectively. For the motor with fractional slot concentrated winding and stator core, the method of tooth separation winding is also adopted. In this method, it can make the windings of each phase not contact each other, and meanwhile benefit fault-tolerant ability between different phases. Furthermore, the physical and thermal isolation between windings can be realized by non-contact between windings. Obviously, there is the natural isolation among each winding, which can enhance the reliability of the electrical machine and drive system.

Open-end winding permanent magnet synchronous machine (PMSM) has been widely used recently [8]. The requirement of the capacity level of the inverter switching devices is reduced, because both sides of the PMSM stator windings are opened. The power is supplied by both-side inverters during the operation. In addition, the open-end winding machine system can be modulated by two-level inverters at both ends of the stator windings to produce three-level effect, which can further improve the machine drive performance and make the control strategy more flexible [9]. There are two kinds of power supply structures about open-end winding machines, i.e. common direct current (DC) bus and isolated bus. The former is more widely used because of its simple structure and low cost. Since the open-end winding with common DC bus provides a zero sequence circuit for zero sequence current flow, the common mode voltage and zero sequence back-electromotive force (EMF) generated by the inverter modulation will generate zero sequence current in the machine winding, which would cause some torque ripples [10].

According to the most recent development of AFPMSM and fault-tolerant machine, there are many researches on radial permanent magnet fault-tolerant machine, but few on axial permanent magnet fault-tolerant machine [6]. The key problems of the fault-tolerant AFPMSM are machine design analysis and fault-tolerant control strategy. Moreover, the key points and difficulties are related to fault detection, resection and operation on the fault status. It is great theoretical and realistic significance for the machine safe and reliable working operation.

This article proposes a fault-tolerant open-end winding MDC-AFPMSM topology for the actuator, which is constrained by the structure, accuracy, reliability and cost. The major contributions of this article are:

- The topology about the machine is discussed and then the redundant design of the stator winding is realized by using the multi-disc laminated structure stator. The polyphase design can be realized by adding the stator and rotor discs, various factors affecting the machine design are fully analyzed.
- A multi-objective optimization function considered the performance, fault tolerance, processing cost, and drive system complexity is proposed. It can determine the phase number of MDC-AFPMSM.
- Taking the case of open-end winding five phase MDC-AFPMSM, main parameter design principle is presented in this article, and key parameters of the machine are calculated. Some basic performance indexes, including the magnetic field distribution, back-EMF, and torque, are analyzed.
- Finally, the fault tolerance under winding short-circuit and open-circuit faults are carefully studied.

Comprehensive simulation results based on 3D finite element algorithm and related analytical discussions are presented to study the drive performance and fault-tolerant ability of the MDC-AFPMSM.

II. TOPOLOGY DESIGN

The design of a MDC-AFPMSM for actuator needs to consider the characteristics of magnetic circuit, winding power converter, and other factors. Different parts of the machine are discussed in the following sections.

A. MACHINE STRUCTURE

The open-end winging MDC-AFPMSM structure is shown in Figure 1. Each stator armature winding of the machine is made of epoxy resin, which is adopted open-end method [12]. Although n sets of armature windings share a controller, each set is driven by an independent driver. A set of armature winding, the corresponding driver and auxiliary components are called a redundancy.

The multi-discs rotors are adopted coaxial output. As shown in Figure 1, N pole and S pole magnetic circuit structure is adopted and the permanent magnets (PMs) are
glued in N pole and S pole pattern. The N and S poles of the PM on both sides of rotor are opposite to each other. The main magnetic circuit starts from one pole, passes through the air gap and stator axially, then passes through the air gap and the adjacent magnetic pole, and finally closes along the rotor yoke, as shown in Figure 2. The magnetic circuit forms an axial series magnetic circuit with the air gap and the stator.

B. POWER DRIVER TOPOLOGY
Different from the traditional multi-disc machine drive topology, $n$ sets of stator windings share a driver, but each set of stator winding is driven by an independent driver. H-bridge drive circuit is used, as depicted in Figure 3 [13]. Each phase winding is operated independently. The machine with fault tolerance can still work normally and reliably by removing the fault channel when the winding happens short-circuit or open-circuit faults. In order to increase the fault tolerance of the machine, this article proposes that each phase winding is composed of several winding discs. Furthermore, the winding discs are the same phase. If one disc in the laminated winding disc fails, the fault can be removed directly by fault-tolerant mechanism, which can ensure the normal operation of the remaining winding discs. Figure 3 shows each phase winding is made up of two parallel winding discs, and each winding disc is driven by an H-bridge inverter. However, the cost and control complexity of the driver would be increased along with the fault tolerance improvement [14].

C. MULTI-OBJECTIVE OPTIMIZATION
The MDC-AFPMSM design is same as the radial PMSM. Various aspects are described in the following sections.

1) BASIC PERFORMANCE
The rated torque, maximum torque, torque ripple and power density should be considered during the design process. The multi-disc machine is adopted to improve performance for satisfying high power output and torque output. There is no cogging torque in MDC-AFPMSM, so the curve of electromagnetic torque is smoothed. Moreover, the amplitude of higher harmonic torque ripple is smaller, which reduces the machine vibrations and noises. Hence, the poly-phase MDC-AFPMSM can reduce the output torque ripple and improve the power and torque output significantly.

2) FAULT TOLERANCE
The machine fault tolerance increases with the number of phases. The traditional three-phase winding with star connection can not continue to work when one phase is out of order. For MDC-AFPMSM, the remaining phase can ensure the stable operation for a long time without stopping the machine when one of these phases suffers fault.

3) PROCESSING COST
There are errors during the MDC-AFPMSM processing. With the increasing number of discs, the cumulative error would grow larger. It is necessary to improve the machining and assembly accuracy. Therefore, the cost would increase with the increase of the number of phases.

4) DRIVE SYSTEM COMPLEXITY
The poly-phase PMSM can reduce the space harmonic content and then harmonic torque can be decreased. However, with the increase of the number of phases, the reduction of harmonic torque is not obvious. On the contrary, the number
of bridge arms of inverter circuit will be increased correspondingly, which makes the control circuit and drive circuit much complex, and also affects the size of stator punching. Therefore, reasonable phase number selection would become one of the major works for the designers.

As mentioned before, the multi-objective function can be written as follow:

$$\text{Max} \{k_1f_1 + k_2f_2 + k_3f_3 + k_4f_4\} \tag{1}$$

where $k_1$, $k_2$, $k_3$, $k_4$ are different weight coefficients respectively, $f_1$ is the basic performance, $f_2$ the fault tolerance, $f_3$ the processing cost, and $f_4$ the drive system complexity.

D. OPTIMIZATION RESULT

The four-phase, five-phase, and six-phase machines are selected in general for the feasibility of practical application [14]. As mentioned regarding the objective function before, the magnetic field intensity, no-load back-EMF, torque and torque ripple of four-phase, five-phase and six-phase machines are analyzed and compared by simulation analysis based on finite element algorithm.

Figure 4 (a) shows the air gap flux density waveform of four-phase, five-phase and six-phase machines. The air gap flux density fundamental amplitude of the three machines is almost the same. The total harmonic distortion (THD) of the air gap flux density of the four-phase machine is 0.38%, and that of five-phase machine is 0.39%. Correspondingly the maximum distortion rate of the air gap flux density of six-phase machine is 0.42%, and that of five-phase machine is the least. The THD of back-EMF about four-phase, five-phase and six-phase machines are observed, as depicted in Figure 4 (b). Figure 4 (b) shows that the worst THD of the back-EMF is 12.10% for four-phase machine, while 8.80% for six-phase machine.

Figure 5 shows the torque characteristics and torque ripples. It is evident that the five-phase machine torque ripple is the minimum (11.98%), which is lower than those of four-phase and six-phase machines under the output torque requirements, 26.19% and 20.67%, respectively.

According to the comparison and analysis of the above and then considering the processing cost, the machining and matching errors will be produced when the related parts of stator and rotor are processed. If just considering the machine errors, the total cumulative error limit of the motor is 0.3 mm. The four-phase machine is composed of nine stator and rotor discs and two left and right end covers, each disc machining accuracy is 0.027 mm. And then, the machining accuracy of five-phase machine is 0.023 mm and that of six-phase machine is 0.02 mm. Relationship between machining error and machining cost is shown in Figure 6. $\Delta$ is the machining error and $Q$ is the processing cost. The processing cost improves along with the increase of phase number. If the assembly error is considered, the cost would increase as the phase number goes up.

As illustrated in Figure 6, the six-phase machine fabrication precision and cost are both the highest with assembly and reliable operation prerequisite. However, the five-phase machine cumulative error is comparatively smaller. Moreover, the THD of air gap flux density and back-EMF of five-phase machine is better, and the torque ripple of five-phase is the least. The complexity of drive system is simpler than the six-phase machine. Then, the five-phase machine is selected for in-depth study with considering the objective function of qualitative analysis.

III. FIVE-PHASE MULTI-DISC CORELESS AFPMSM DESIGN

As mentioned above, this article takes five-phase open-end winding MDC-AFPMSM as an example. First of all, the topology is shown in Figure 7. Then the parameter design principle is presented. The air gap flux density is optimized by the finite element algorithm. Finally, main parameters are considered after the optimization process.
If the electric loading at the average diameter of stator \( A_{av} \) is considered, the electromagnetic power \( (P_{em}) \) of the disc PMSM can be obtained by [15]

\[
P_{em} = EI\eta = \frac{\pi^2}{480} n B_{kav} A_{av} \left( D_{mo}^2 - D_{mi}^2 \right) \left( D_{mo} + D_{mi} \right)
\]  

(2)

where \( E \) is electromotive force effective value, \( I \) is current effective value, \( \eta \) is the efficiency of machine, \( B_{kav} \) is the average value of air gap flux density under one pole pitch, \( D_{mo} \) is outer diameter of PM, \( D_{mi} \) is inner diameter of PM.

Using (2), it can be written as:

\[
\frac{D_{av}^2 L_{ef} n}{P_{em}} = 60 \times 10^4 \frac{\pi^2 B_{kav} A_{av}}{B_{kav} A_{av}} = 6.1 \times 10^4
\]

(3)

Then the power per unit volume can be obtained by

\[
\frac{P_{em}}{V} = \frac{P_{em}}{\pi D_{av} L_{ef} \sum h} = \frac{\pi}{120} n B_{kav} A_{av} \left( \frac{D_{av}}{\sum h} \right) \times 10^{-4}
\]

(4)

where \( D_{av} \) is the average diameter, \( D_{av} = (D_{mo} + D_{mi})/2 \), \( L_{ef} \) is the effective length of armature winding conductor, \( \sum h \) is the total axial length of machine. As can be seen, the power per unit volume of the disc PMSM is directly proportional to the average diameter of the armature and inversely proportional to the total axial length.

The main dimensions of the machine can be calculated as:

\[
L_{ef} = D_{mo} - D_{mi} \quad \text{and} \quad D_{av} = \frac{D_{mo} + D_{mi}}{2}
\]

where \( \gamma = D_{mo}/D_{mi} \) is the ratio of outer diameter and inner diameter of PM.

Considering the maximal constraints based on (5), it can get as:

\[
\gamma = \frac{D_{mo}}{D_{mi}} = \sqrt{3}
\]

(6)

The diameter ratio of the disc PMSM is between 1.5 and 2.2. Considering the leakage flux and edge effect, the diameter ratio is selected as 1.8.

**B. ROTOR**

The selection of PM material is very important during the machine design process. It needs to meet some requirements, such as good mechanical property, easy to process, low cost, and so on. Moreover, the better magnetic performance can provide corresponding magnetic field intensity. Due to the large equivalent air gap length of disc coreless machine, high performance PM with high air gap flux density is needed. Nd-Fe-B material not only has good mechanical properties and low cost, but also has high remanence density and coercivity. The brand N38 with 1.24 A/m remanence density, 955 kA/m coercivity and 1.033 relative permeability is considered in this article.

The THD of air gap flux density, the waveform of back-EMF, torque and loss are affected by the shape of PM. The PMs of the most AFPMSM adopt sector or cylindrical structure. In addition, the fan-shaped PM has higher space utilization than cylindrical PM. The fan-shaped PM is shown as Figure 8.

The finite element model of permanent magnet with different pole arc coefficients is established. Figure 9 shows the air gap flux density along the radius. The air gap flux density with pole arc coefficient from 0.57 to 0.83 is fully analyzed by Fourier transform. The results show that the fundamental amplitude of air gap flux density is changed little, but the THD of the air gap flux density is variable under different pole arc coefficients, as shown in Figure 10.

It can be seen from Figure 10 that with the increase of pole arc coefficient, the THD of air gap flux density decreases firstly and then increases gradually. When the value of pole arc coefficient is 0.81, the THD is only 0.33% and
The waveform is pretty sinusoidal. Therefore, the pole arc coefficient is finally considered as 0.81 in this article.

C. YOKE

The leakage flux distribution of disc machine is complex. Unlike conventional disc machine, the leakage flux of the disc coreless machine is mainly composed of two parts: one is the leakage flux \( \phi_1 \) on the back of two permanent magnets, the other is the leakage flux \( \phi_2 \) between the two adjacent poles. In general, \( \phi_1 \) is affected by the yoke thickness. The yoke thickness not only meets the air gap magnetic field requirements, but also considers the saturation of the yoke. The yokes of this machine is composed of both-side yokes and middle yokes, as shown in Figure 11(a).

In order to get the most suitable yoke thickness, the air gap flux density of the machine with different yoke thickness is analyzed by the finite element algorithm, as depicted in Figure 11(b) and Figure 11(c).

As shown in Figure 11(b), the air gap flux density changes little along with the increasing of the thickness of the both-side yokes. On the other hand, the THD of the air gap flux density decreases firstly and then increases gradually. The minimum value of THD is 0.28% when the both-side yokes are selected 5 mm. As can be seen from Figure 11(c), air gap flux density changes very little. The THD change trend is similar as those of both-side yokes. The minimum THD value is 0.29% when the middle yoke thickness is 7.5 mm. Therefore, the middle yoke thickness is considered as 7.5 mm in this article.

D. STATOR

The winding of disc coreless permanent magnet synchronous machine is wound winding, which is fixed by epoxy resin without magnetic conduction. Therefore, there is no stator core in this kind of machine, and the arrangement of winding is not limited by cogging torque [16]. These features can reduce the weight of stator, which can reduce some eddy current loss and hysteresis loss.

Laminated windings and non-laminated windings are widely used. The winding arrangement of non-laminated concentrated winding is not coincident with each other and close to each other. According to the existing technique, the copper consumption of non-overlapping concentrated winding is 15% less than that of laminated winding. In addition, the THD of the back EMF with non-laminated concentrated windings is much more significant than that of machine with the laminated windings [11]. Concentrated windings can reduce the amount of end winding of iron core, and increase the utilization of material and space. Therefore, the non-laminated concentrated winding is considered in this article.

The number of coils per layer is \( Z_0/2 \), and the number of coils per phase \( n_c = Z_0/(2m) \), where \( Z_0 \) is the number of stator slots, \( m \) is the phase number. If the number of coils per layer is \( Z_0 \), it will get \( n_c = Z_0/(m) \).

Then, the number of slots per pole can be expressed as:

\[
Q_1 = \frac{Z_0}{2p} \tag{7}
\]

The number of slots per pole per phase can be calculated from:

\[
q_1 = \frac{Z_0}{2pm} \tag{8}
\]

The number of conductors per coil of single-layer winding can be decided by

\[
N_c = \frac{\alpha_p \alpha_{\omega} N_1}{n_c} = \frac{\alpha_p \alpha_{\omega} N_1}{pq_1} \tag{9}
\]

where \( N_1 \) is the turns in series per phase, \( \alpha_p \) the parallel branches, and \( \alpha_{\omega} \) is the parallel conductors.

E. MAIN PARAMETERS

According to the design requirements, one five-phase MDC-AFPMMSM with 800 W power and 3000 r/min rated speed is designed. Table 1 depicts main specifications of the MDC-AFPMMSM.
TABLE 1. Main specifications of the MDC-AFPMSM.

| Parameters            | Value     |
|-----------------------|-----------|
| Rated torque          | 2.5 [Nm]  |
| Rated frequency       | 250 [Hz]  |
| Rotor inner diameter  | 60 [mm]   |
| Rotor outer diameter  | 110 [mm]  |
| PM thickness          | 5 [mm]    |
| Pole arc coefficient  | 0.81      |
| Yoke thickness        | 5/7.5 [mm]|
| Air gap height        | 5 [mm]    |
| PM material           | NdFe38    |
| Yoke material         | 10#Steel  |
| Pole number           | 10        |
| Winding turn          | 30        |

FIGURE 12. Flux density: (a) ir gap distribution, (b) circumferential flux density, an (c) xial flux density.

IV. MACHINE PERFORMANCE ANALYZE

The flux density of the MDC-AFPMSM is analyzed by the finite element algorithm, as shown in Figure 12.

The air gap A, B, C, D and E are shown in Figure 12(a). Figure 12(b) shows circumferential flux density at average radius. The transverse axis in Figure 12(b) is the arc length, and the longitudinal axis is the radial magnetic density at the corresponding arc length. The waveform of circumferential air gap flux density is very close to sinusoidal. The axial air gap magnetic field along the radial direction, starting at 20 mm from the center of the circle and ending at the position 60 mm away from the center of circle, is depicted in Figure 12(c). The longitudinal axis is the axial magnetic density at the corresponding radius. The flux density decreases sinusoidally from the center of the PM to all directions, as shown in Figure 12(c).

As described earlier, the flux density of the air gap length A, B, C, D, and E under no-load condition is about 0.9 T, which shows that the PM can work near the point with maximum magnetic energy product. As shown in Figure 13, the maximum flux density is red on the yoke. In addition, the magnetic flux density decreases gradually from inside to outside along the radius. The arrows in Figure 14 show the direction of the machine main flux loop.

In Figure 15, based on finite element algorithm, the results of no-load back-EMF are shown by the solid lines. Figure 15(a) shows the no-load back-EMF waveform of five channels at the rated speed of 3000 r/min, and the amplitude...
is about 198.39 V. Figure 15(b) shows the Fourier analysis. The back-EMF of five windings is in the same phase, and the amplitude is equal within the allowable error range.

The waveform of torque is shown in Figure 16. The average torque is about 2.79 Nm, the maximum and minimum torque is 2.95 Nm and 2.62 Nm, respectively, and the torque ripple is 11%.

V. FAULT TOLERANCE ANALYZE

The MDC-AFPMSM not only possesses strong overload capacity and small torque ripple, but also gets strong physical isolation, magnetic isolation, thermal isolation and electrical isolation.

In the proposed five phase MDC-AFPMSM with open-end windings, each phase armature winding of the five phase is differred by 72°. Moreover, terminals are led out respectively to form five independent channels and the channels are physically isolated. The five channels share one main flux loop, but the large air gap and the magnetic isolation effect of the middle rotor can reduce the electromagnetic coupling between the channels. Each phase winding can adopt H-bridge inverter based driver, which suppresses the ill influence of fault relative to normal phase. It can get the electrical isolation function between each phase winding [18].

The stator disc in the MDC-AFPMSM is only wounded with one-phase concentrated winding, while the traditional distributed winding inevitably leads winding contact. Due to the winding contact short circuit, the two-phase winding will fail at the same time. Furthermore, once one-phase winding happens short-circuit, the heat generated by the phase winding is transferred easily to the other coil. And then the normal phase winding insulation life is affected. Therefore, the winding contact short-circuit fault is one of the most serious faults. It is useful to avoid the physical contact between the winding and short-circuit by the adopted concentrated winding with one-phase.

In order to verify the fault tolerance of the machine, the fault-tolerant control algorithm is not considered in this article.

A. OPEN CIRCUIT FAULT

It is assumed that phase-A winding suffers open-circuit fault, and the machine changes from five-phase operation to four-phase operation. The torque of the machine is analyzed by finite element algorithm, as shown in Figure 17. The average torque is 2.25 Nm and the ripple of the torque is 60%. The fault torque decreases 19.35% compared with normal state torque. In addition, the torque ripple is 60% by the finite element algorithm, as shown in Figure 18. From the results, the machine can still work reliably until the fault is removed. Moreover, phase-A and B windings short-circuits are assumed to suffer simultaneously, in which the average torque is 1.75 Nm and the torque ripple is 59%. The fault torque is 37.2% smaller than the normal state torque. In the same way, the machine can still work dependably until the fault is removed. The result is depicted as Figure 18.

The current will increase when all internal coils of phase-A winding suffers short-circuit. The armature reaction is produced due to the increased current. In order to study whether the larger current affects the machine magnetic circuit or not, the air gap flux density of the phase-A winding is analyzed by using the finite element algorithm, as shown in Figure 19. The air gap flux density of the machine has almost no change by Fourier analysis. Therefore, from the aforementioned results, the flux density of the machine is almost not affected when the phase-A winding internal coils are all in short-circuit. By full investigation, this result is due to the mild armature reaction caused by the large magnetic resistance of coreless machine.

When the internal coils of phase-A and B windings are all in short-circuit, the greater current will be generated. The air gap flux density of phase-A and B is analyzed by finite
element algorithm, as depicted in Figure 20. The flux density of the normal phase is very little affected when the internal coils of phase-A and B windings are all in short-circuit, which thanks to the high magnetic resistance of the machine.

VI. CONCLUSION
In this article, a multi-disc coreless axial flux permanent magnet synchronous machine (MDC-AFPMSM) with N pole and S pole type series magnetic circuit and open-end winding is proposed for high reliability applications. A multi-objective optimization function is driven for the AFPMSM design. Moreover, a full detailed design procedure for AFPMSM has been introduced in this article. The flux density, back-EMF, torque and fault tolerance of the AFPMSM are studied using 3D finite element algorithm so that its functionality is substantiated. Comprehensive simulation results have fully demonstrated that the MDC-AFPMSM has advantages of reliability, mild armature reaction, simple construction, which is very attractive for the industrial applications with requirements of strong fault-tolerant ability.

REFERENCES
[1] G. Puchner and N. Richmond, “Electromagnetic actuators in context of industrial and social development from yesterday to tomorrow,” in Proc. 16th Int. Conf. New Actuat., Bremen, Germany, Jun. 2018, pp. 1–4.
[2] F. Liu, D. Xu, M. Liu, S. Zhang, and J. Dai, “Fault diagnosis and fault tolerant control for the actuator of marine vehicles,” in Proc. Oceans Taipei, Apr. 2014, pp. 1–5.
[3] T. Feng, S. Hao, X. Zhang, T. Yang, and L. Wang, “Development of a fault-tolerant permanent-magnet synchronous motor,” IEEE Access, vol. 7, pp. 146228–146239, 2019.
[4] M. Wang, C. Tong, Z. Song, J. Liu, and P. Zheng, “Performance analysis of an axial magnetic-field-modulated brushless double-rotor machine for hybrid electric vehicles,” IEEE Trans. Ind. Electron., vol. 66, no. 1, pp. 806–817, Jan. 2019.
[5] L. Zhang, X. Zhu, J. Gao, and Y. Mao, “Design and analysis of new five-phase flux-intensifying fault-tolerant interior-permanent-magnet motor for sensorless operation,” IEEE Trans. Ind. Electron., vol. 67, no. 7, pp. 6055–6065, Jul. 2020.
[6] B. Wang, J. Wang, B. Sen, A. Grillo, Z. Sun, and E. Chong, “A fault-tolerant machine drive based on permanent magnet-assisted synchronous reluctance machine,” IEEE Trans. Ind. Appl., vol. 54, no. 2, pp. 1349–1359, Apr. 2018.
[7] A. Dwivedi, S. K. Singh, and B. K. Srivastava, “Analysis and performance evaluation of axial flux permanent magnet motors,” IEEE Trans. Ind. Appl., vol. 54, no. 2, pp. 1765–1772, Mar. 2018.
[8] E. Levi, I. N. W. Satiawan, N. Bodo, and M. Jones, “A space-vector modulation scheme for multilevel open-end winding five-phase drives,” IEEE Trans. Energy Convers., vol. 27, no. 1, pp. 1–10, Mar. 2012.
[9] Z. Q. Zhu, B. Lee, and X. Liu, “Integrated field and armature current control strategy for variable flux reluctance machine using open winding,” IEEE Trans. Ind. Appl., vol. 52, no. 2, pp. 1519–1529, Apr. 2016.
[10] W. Hu, C. Ruan, H. Nian, and D. Sun, “Simplified modulation scheme for open-end winding PMSM system with common DC bus under open-phase fault based on circulating current suppression,” IEEE Trans. Power Electron., vol. 35, no. 1, pp. 10–14, Jan. 2020.
[11] W. Geng and Z. Zhang, “Analysis and implementation of new ironless stator axial-flux permanent magnet machine with concentrated nonoverlapping windings,” IEEE Trans. Energy Convers., vol. 33, no. 3, pp. 1274–1284, Sep. 2018.

XIAO GUANG WANG received the B.S. degree in electrical engineering from the Hebei University of Technology, Tianjin, China, in 2006, the M.S. degree in control theory and control engineering from Xihua University, Chengdu, China, in 2010, and the Ph.D. degree in electrical engineering from Tianjin University, Tianjin, in 2015.
He is currently a Lecturer with the School of Electrical and Electronic Engineering, Hubei University of Technology. His research interests include electrical machines and motor drives.
MENG ZHAO received the B.S. degree in electrical engineering from the Henan University of Urban Construction, Pingdingshan, China, in 2018. She is currently pursuing the M.S. degree in electrical engineering with the Hubei University of Technology. Her research interest includes electrical machines design.

LEI TANG received the B.E. and M.E. degrees from Sichuan University, Chengdu, China, in 2011 and 2014, respectively, and the Ph.D. degree from the State Key Laboratory on Electrical Insulation and Power Equipment, Xi’an Jiaotong University, Xi’an, China, in 2020, all in electrical engineering.

He is currently a Lecturer with the School of Electrical Engineering, Southwest Jiaotong University, China. His research interests include power system planning and the optimization of electrical drive systems.

WEI XU (Senior Member, IEEE) received the B.E. and M.E. degrees from Tianjin University, Tianjin, China, in 2002 and 2005, respectively, and the Ph.D. degree from the Institute of Electrical Engineering, Chinese Academy of Sciences, in 2008, all in electrical engineering.

From 2008 to 2012, he was a Postdoctoral Fellow with the University of Technology Sydney, a Vice Chancellor Research Fellow with the Royal Melbourne Institute of Technology, Japan, and a Science Promotion Society Invitation Fellow with Meiji University. Since 2013, he has been a Full Professor with the State Key Laboratory of Advanced Electromagnetic Engineering, Huazhong University of Science and Technology, China. He has more than 100 articles accepted or published in the IEEE TRANSACTIONS Journals, two edited books published by Springer Press, one monograph published by China Machine Press, and 120 invention patents granted or pending, all in the related fields of electrical machines and drives. His research interest includes design and control of linear/rotary machines.

MD. RABIUL ISLAM (Senior Member, IEEE) received the Ph.D. degree in electrical engineering from the University of Technology Sydney (UTS), Sydney, Australia, in 2014.

He was appointed as a Lecturer at RUET in 2005, where he was promoted to a Full Professor, in 2017. In early 2018, he joined the School of Electrical, Computer, and Telecommunications Engineering (SECTE), University of Wollongong (UOW), Wollongong, Australia. His research interests include power electronic converters, renewable energy technologies, power quality, electrical machines, electric vehicles, and smart grid. He has authored or coauthored more than 170 articles, including 48 IEEE TRANSACTIONS/IEEE Journal articles. He has written or edited four technical books published by Springer. He has received several funding from Government and Industries, including the Australian Government ARC Discovery Project 2020 entitled "A Next Generation Smart Solid-State Transformer for Power Grid Applications." He has served as a Guest Editor for the IEEE TRANSACTIONS ON ENERGY CONVERSION, the IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, and IET Electric Power Applications. He has been serving as an Editor for the IEEE TRANSACTIONS ON ENERGY CONVERSION and the IEEE POWER ENGINEERING LETTERS, and an Associate Editor for IEEE ACCESS.