Auxiliary Teeth Design to Reduce Short-Circuit Current in Permanent Magnet Generators

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Abstract—In this paper, a new auxiliary teeth structure is proposed for fault-tolerant permanent magnet (PM) generators, which can reduce the short-circuit currents. Firstly, the short-circuit current and the phase to phase isolation of the fault-tolerant generator are analyzed briefly. Secondly, the auxiliary teeth structure is optimized to improve fault-tolerant capability. Then, the PM generators with different stator structures are compared to evaluate the proposed auxiliary teeth structure. Four critical generator parameters are investigated, i.e. back-electromotive forces, short-circuit currents, stator magneto motive force (MMF) harmonics, and torque performances. The results show that the proposed structure has better fault-tolerant capability than the conventional two-layer windings. Moreover, the stator MMF harmonics can be suppressed. Furthermore, the cogging torque and torque ripple can be suppressed by adopting the proposed structure. Finally, the simulated results are given to validate the theoretical analysis.

Index Terms—Auxiliary teeth, fault-tolerant generator, magneto motive force, torque, finite-element method, permanent magnet generator.

I. INTRODUCTION

Due to high reliability and high efficiency, multi-phase permanent magnet (PM) generators have attracted more attentions for aviation applications, e.g., more electric aircrafts and all electric aircrafts (AEAs) [1]-[3]. Multi-phase generators with fractional-slot concentrated windings can further improve the fault-tolerant capability. The proposed fault-tolerant PM generator is applied in the power supply system of an AEA. For AEA generators, when a short-circuit fault occurs, its currents will increase significantly. It will promote a safety hazard and finally result in overheating and even burn the generator systems [4]-[6]. To relieve this risk, the amplitude of the short-circuit current should be retained within a threshold value. Besides, the amplitude of the short-circuit current is also a critical reference index in the PM generator design [7]-[9]. Thus, the short-circuit current should be limited to improve the reliability of the PM generator.

For the design principle of fault-tolerant PM generators, electrical, magnetic, thermal, physical isolation features are listed as the most essential ones. On generator design level, many published literatures have investigated methods of reliability enhancement in the PM generators. Single-layer windings and fractional-slot concentrated windings are usually used for fault-tolerant PM generators. In particular, single-layer windings can provide additional magnetic circuit for armature windings to improve fault-tolerant capability [10]-[12]. However, these methods are aimed at improving fault-tolerant capability by adjusting winding topologies. It will introduce new MMF harmonic components and inevitably lower torque performance. Besides, the single-layer winding is only suitable for the low-power generators less than 10kW. For fractional-slot concentrated winding generators, the stator magneto motive force (MMF) harmonics are abundant, which will lead to the iron loss and temperature rise [13]-[15]. The effect of the stator MMF harmonics has been neglected, which is introduced by fault-tolerant design.

In this paper, a new auxiliary teeth structure will be proposed, which can meet the requirement of the above isolation features and suppress the stator MMF harmonics. Also, it can improve the fault-tolerant capability of PM generators. First, the short-circuit current and the phase to phase isolation are analyzed. The size of the auxiliary teeth is determined for the purpose of high fault-tolerant capability. Second, the PM generators with different stator structures are compared fairly to verify the feasibility of the auxiliary teeth structure. Then, four critical characteristics of the fault-tolerant PM generators, including back-electromotive forces (EMFs), short-circuit currents, stator MMF harmonics and torque performances are evaluated. Finally, the simulated results are given to validate the auxiliary teeth structure.

Fig. 1. Designed fault-tolerant PM generator.
stator structure consists of two types of stator teeth, namely armature teeth and auxiliary teeth, while the auxiliary teeth are placed in the middle of the armature teeth. The surface mounted PMs are fixed by card teeth. The type of stator armature teeth is parallel tooth and stator slot space is trapezoid. The space at bottom of the stator slot is smaller than the trapezoid auxiliary teeth, when adopted the rectangular teeth. Therefore, we adopt the trapezoid auxiliary teeth to match the winding arrangement to ensure the slot filling factor. To avoid stator saturation, armature teeth have been enlarged. From Fig. 2, the length of auxiliary teeth is expressed by $L_a$. $W_a$ is the center width of auxiliary teeth which defined as half of the sum of two bottom margins of the auxiliary teeth.

Fig. 2. Shape of the auxiliary teeth structure.

In order to obtain high reliability and high efficiency of the PM generators, the feasible slot-pole combinations are discussed. With the advantages of short windings end, large self-inductance, and small mutual-inductance, fractional-slot concentrated windings are suitable for fault-tolerant generators. Slot-pole combinations of fault-tolerant PM generators are listed in Tab. I. The 10-pole/12-slot has the better fault-tolerant capability and lower total harmonic distortion (THD) than the competitive slot-pole combinations. The greatest common divisor of the slot number and pole number is selected as 2 to reduce cogging torque. Therefore, the 10-pole/12-slot combination is adopted for the fault-tolerant PM generators.

Meanwhile, the appropriate phase shift is also discussed to improve fault-tolerant capability. For the 10-pole/12-slot PM generator, phase shift can be selected as 30° and 60°, respectively. Correspondingly, they are named as asymmetric windings and symmetrical windings. Fig. 3 exhibits the concrete winding arrangements and EMF phasor diagrams of the above winding connections. The positive sectors of phases A1 and A2 are labeled as A1+, A2+. Similarly, for the negative sectors, the letters A1- and A2- are used. The short-circuit current of 60° phase shift is smaller than that of the 30° phase shift, as shown in Fig. 4. Therefore, the auxiliary teeth structure combined with symmetrical dual 3-phase windings is adopted to obtain high fault-tolerant capability.

### III. FAULT-TOLERANT EVALUATION

To verify the feasibility of the auxiliary teeth structure, the 10-pole/12-slot symmetrical dual 3-phase windings surface mounted PM generator is designed. Finite-element method (FEM) is used to evaluate the fault-tolerant capability and the electromagnetic performance. The air-gap length amounts to 1.2 mm. The rated speed of the PM generator is 6500r/min. The PMs needs to be fixed with a sheath, which takes up air-gap length. The main parameters of the fault-tolerant PM generator are listed in Table II.

![Fig. 3. Winding arrangements and EMF phasor diagrams. (a) Symmetrical windings. (b) Asymmetric windings.](image)

![Fig. 4. Steady short-circuit currents of different phase shifts.](image)

### TABLE I

| Slot-Pole Combinations of PM Generators | Windings factor | Torque (Nm) | Short-circuit current (A) | THD % |
|----------------------------------------|----------------|------------|--------------------------|-------|
| 9/6 3                                  | 0.866          | 33.1       | 118                      | 15.1  |
| 9/8 3                                  | 0.945          | 40.6       | 96                       | 3.3   |
| 12/8 3                                 | 0.866          | 34.2       | 122                      | 13.8  |
| 12/10 Dual-3                           | 0.966          | 41.3       | 50                       | 4.1   |
| 12/10 6                                | 0.933          | 40.5       | 42                       | 2.9   |

### TABLE II

| Main Parameters of Fault-Tolerant PM Generator | Symbol | Quantity | Value |
|-----------------------------------------------|--------|----------|-------|
| $D_o$ Outer stator diameter (mm)               | 167    |
| $D_i$ Inner stator diameter (mm)               | 110    |
| $L$ Axial length of stator core (mm)           | 60     |
| $h_{pm}$ PM thickness (mm)                     | 5      |
| $p$ Number of pole                            | 10     |
| $N_s$ Number of stator slots                   | 40     |
| $g$ Air-gap length (mm)                        | 1.2    |
| $P$ Rated output power (kW)                    | 26     |
| $m$ Number of phase                            | 6      |
| $n$ Rated speed (r/min)                        | 6500   |
The short-circuit current is a critical parameter of fault-tolerant generators. To evaluate the short-circuit current, the characteristic current $I_{ch}$ is introduced, which can be calculated as

$$I_{ch} = \frac{\lambda_{PM}}{L_d} \quad (1)$$

where $\lambda_{PM}$ is the flux linkage generated by PM field and $L_d$ is the $d$-axis inductance. Fig. 4 presents the schematic of maximum voltage and current trajectory of fault-tolerant PM generators. $I_1$ is the rated current and $I_{ch}$ is the center of voltage-limit ellipses in the rotor referred $d$-$q$ current plane. The value of the $I_{ch}$ is approximately equal to the $I_{sc}$. Through the schematic diagram, the multiple of short-circuit current can be calculated qualitatively. Methods of reducing the multiple of short-circuit current are also obtained. It can be reduced by increasing the electrical load and reducing the magnetic load. Specially, when the $I_{ch}$ is equal to $I_1$, the short-circuit current can be reduced theoretically to the rated current. At this time, the multiple of short-circuit current is equal to 1. The short-circuit current for different stator structures can be obtained from the voltage model in Fig. 6 and solved as

$$I_{sc} = \frac{E_0}{\omega L_s} \quad (2)$$

where $E_0$ is the no-load back-EMF, $\omega$ is the electrical angular speed, $L_s$ is the inductance. It is noted that (2) can be simplified by ignoring the resistance and the leakage reactance of the PM generator. The specific short-circuit current was derived in [16]. From (2), it can be known that the short-circuit current actually depend on the no-load back-EMF and the inductance. Therefore, the short-circuit currents should be analyzed from the perspectives of no-load back-EMF and inductance. Also, these two parameters are closely related to the electric load and magnetic load and can be calculated by FEM. The phase isolation $m_t$ refers to the coupling of adjacent phases. When the PM generators experience a single-phase fault, the fault phase will affect normal operation of other phases. This will deteriorate the whole generator system. It is necessary to reduce the phase isolation of fault-tolerant generators. The phase isolation $m_t$ is calculated as

$$m_t = \frac{L_{AA}}{L_{AB}} \times 100\% \quad (3)$$

where $L_{AA}$ is the self-inductance of A-phase winding and $L_{AB}$ is the mutual-inductance between A-phase and B-phase. From (3), it can be known that the fault-tolerant PM generators require larger self-inductance and lower mutual-inductance than those of the conventional PM generators.

Based on the above theoretical analysis, it can be known that the fault-tolerant capability is closely related to the inductance of the PM generator. The function of the auxiliary teeth is to improve fault-tolerant capability by adjusting the inductance. Moreover, the auxiliary teeth structure has a great influence on the inductance. Therefore, the auxiliary teeth structure is optimized by adjusting the size of the auxiliary teeth for high fault-tolerant capability. By using FEM, the inductances with different sizes of the auxiliary teeth are analyzed. It can be known that the fault-tolerant capability increases linearly with the width of the auxiliary teeth. However, the slot filling factor and power density will reduce greatly, when the width exceeds 2 mm. Similarly, the length of the auxiliary teeth can be obtained. Fig. 7 presents the variation of inductances with the lengths of the auxiliary teeth. It can be seen that the value of the mutual-inductance rebounds when the length exceeds 20 mm. Meanwhile, the self-inductance also reports a sluggish growth.

According to the above analysis, the short-circuit current and the phase to phase isolation of different sizes of the auxiliary teeth can be calculated. Fig. 8 shows the short-circuit current and torque with different widths of the auxiliary teeth. It can be seen that the short-circuit current is reduced with the width increasing of the auxiliary teeth. Specially, the torque decreases significantly when the width exceeds 2 mm. Finally, the width of the auxiliary teeth is selected as 2 mm.
Fig. 7. Comparisons of inductances with different lengths of the auxiliary teeth. (a) Mutual-inductance. (b) Self-inductance.

Fig. 9 shows the short-circuit current and the phase to phase isolation with different lengths of the auxiliary teeth. It should be noted that the length varies from 12 mm to 22 mm. The steady short-circuit current can be reduced to 26 A. Also, the phase to phase isolation can be reduced to 0.6 %. However, due to the rebounding of the mutual-inductance, the phase to phase isolation increases. At this time, the length of the auxiliary teeth is 20 mm. This result coincides with the inflection point of the mutual-inductance in Fig. 7. Therefore, the length of the auxiliary teeth should not exceed 20 mm. Finally, the length and width of the auxiliary teeth are determined as 20 mm and 2 mm, respectively. It can be known that it is effective to improve the fault-tolerant capability by optimizing the auxiliary teeth structure.

Fig. 8. Short-circuit current and torque performance vary with width of the auxiliary teeth.

Fig. 9. Short-circuit currents and phase isolation vary with length of the auxiliary teeth.

IV. PERFORMANCE COMPARISON

After the size is determined, the influence of the auxiliary teeth on stator MMF harmonics and electromagnetic performance is considered. Therefore, the proposed auxiliary teeth generator is comparatively investigated with different stator structures, as presented in Fig. 10. They have conventional two-layer windings and two-layer windings with the auxiliary teeth, respectively. Four critical parameters of fault-tolerant PM generators including back-EMFs short-circuit currents, stator MMF harmonics, and torque performances are investigated. For a fair comparison, all these fault-tolerant PM generators are developed with same size, slot filling factor, electromagnetic loading, material and operating environment.

A. Back-EMF

From the previous analysis, short-circuit currents are closely related to the back-EMFs. The content of back-EMF harmonics also has a great influence on the power quality of the whole generator system. For fault-tolerant generators, excessive PM magnetic field ends up with a great increase in short-circuit currents when a short-circuit fault occurs. To reduce this risk, the maximum back-EMF so as the PM magnetic field should be limited. Fig. 11 compares the no-load back-EMFs of the fault-tolerant PM generators with different stator structures. It can be seen that the maximum back-EMF is limited and the proposed structure consists of relatively lower back-EMF than the conventional one. Moreover, the proposed structure also reduces the THD of the back-EMF, which is an important design index of PM generators. The main harmonic components of the back-EMF waveform comprise the 3rd and 5th harmonics. To evaluate the sinusoidal shape, THD is introduced and can be calculated as

$$\text{THD} = \sqrt{\sum_{n=2}^{\infty} \frac{U_n^2}{U_1^2}}$$

where $U_n$ is the amplitude of the back-EMF harmonic. $U_1$ is the fundamental component. From (4) and Fig. 11, the THDs of the conventional and the proposed auxiliary teeth generators can be calculated as 2.9 % and 2.8 %, respectively. With the auxiliary teeth structure, the amplitude and the THD of the back-EMF are all reduced. Besides, the THD of back-EMFs can be further reduced by skewing stator slots [17], [18].

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B. Short-Circuit Current

From Section II, it can be known that the short-circuit current can be suppressed significantly by using the appropriate auxiliary teeth. The steady short-circuit current and the peak short-circuit current are evaluated by FEM and the waveforms in Fig. 12. It should be noted that the steady short-circuit current is predicted when the flux of short-circuit windings is minimum. The peak short-circuit current is predicted when the flux is maximum. It can be observed that both the steady and peak short-circuit current of the proposed structure are lower than those of the conventional two-layer windings. This result is consistent with the above analysis. After the modulation of the auxiliary teeth, the steady short-circuit current is reduced from 42 A to 32 A, and the peak short-circuit current is reduced from 86 A to 63 A. The decrease reached 23 % and 27 %, respectively.

Fig. 13 presents that the inductances of the PM generators with different stator structures. It can be seen that the proposed structure has larger self-inductance and also lower mutual-inductance between two adjacent phases, compared to the conventional two-layer windings. Therefore, the auxiliary teeth structure is more suitable for fault-tolerant PM generators. Also, this is the reason why the short-circuit current and the phase to phase isolation can be reduced by adopting the auxiliary teeth. Moreover, smaller short-circuit currents also result in smaller braking torque. Each slot of the above stator structures contains two coil sides, which will increase the risk of short circuit between phases. Furthermore, short-circuit currents might interfere other normal phases. The auxiliary teeth structure can completely avoid phase to phase short-circuit fault. Also, the phase to phase isolation can be reduced from 8 % to 0.6 %, which reduces the risk of fault phase and retains the scope of security. For AEA applications, the proposed fault-tolerant PM generators have overall better fault-tolerant capability, compared to the conventional PM generators.

C. MMF Harmonic Analysis

Due to short winding end, large self-inductance, small mutual-inductance and low short-circuit current, single-layer fractional-slot concentrated windings is the first choice of fault-tolerant PM generators. Since only one effective side of the winding coil is placed in a slot, no interlayer insulation is needed. However, for conventional fault-tolerant PM generators, the stator MMF harmonics cannot be suppressed by selecting suitable short pitch coil winding and winding connections. Besides, rich stator MMF harmonics will lead to temperature rise and core loss. Meanwhile, such a large harmonic content can drastically influence the performance of PM generators. Specifically, it can reduce the power factor and efficiency of fault-tolerant PM generators. However, the power factors of the proposed structure and conventional structure are 0.87 and 0.88, respectively. The power factor is reduced slightly when using the proposed structure. In order to evaluate the effect of the auxiliary teeth on stator MMF harmonics, the spectrums of the stator MMF harmonics with different stator structures are compared, as shown in Fig. 14. It can be observed that the 1st order is the lowest stator MMF harmonic and the...
amplitude of the auxiliary teeth is lower than that of the conventional one. Also, the high-order components can be suppressed by the proposed auxiliary teeth. It is a common knowledge that the stator MMF harmonics reduction has profound influence on the core loss. Moreover, the core loss can be reduced because of the suppression of stator MMF harmonics. The core loss produced by the 1st order MMF harmonics is reduced from 167 W to 132 W attributing to the auxiliary teeth structure. Meanwhile, the temperature of the PM generators can also be reduced.

Furthermore, the auxiliary teeth can also be employed as the cooling-teeth. The heat dissipation capacity of the PM generator can be improved with the auxiliary teeth. In order to investigate the influence of the auxiliary teeth on the heat dissipation, the temperature distributions of different stator structures are compared, as shown in Fig. 15. For a fair comparison, the temperature is simulated, when the generators operate with the same cooling model, output and operating environment. It should be noted that the cooling mode is housing water-cooling. It can be seen that the maximum temperature is concentrated in the middle of the stator slot which decreases from 101 °C to 93 °C by using the auxiliary teeth. Also, the temperature of other parts decreases greatly. Finally, the results show that the stator MMF harmonics can be suppressed by the auxiliary teeth. Meanwhile, the heat dissipation capacity of the fault-tolerant PM generators can be improved.

D. Electromagnetic Torque

In general, when the PM generators experience a short-circuit fault, its currents will increase greatly. This will lead to the magnetic circuit saturation and thereby deteriorate the torque performance of the whole generator system. Besides, the torque capability will be affected by adopting the auxiliary teeth. Thus, the torque performance of PM generators is essential to evaluate for AEA applications. It is noted that the torque performances are calculated based on the electric machine condition. Fig. 16 compares the waveforms of torques with different stator structures, showing that the torque ripple of the proposed structure is 4.1 %, smaller than that of the conventional one. Though the average torque is reduced, the auxiliary teeth structure makes the torque ripple smaller. Fig. 17 compares the cogging torque waveforms of the conventional and proposed structures. As shown, the peak cogging torque of the proposed structure is 0.4 Nm, which has a reduction of 33 % than the conventional one. Since the number of the stator slots is increased by adopting the auxiliary teeth, which is similar to the method of opening stator virtual slots [19], [20]. Therefore, the torque ripple and the cogging torque can be reduced.

V. Conclusions

In this paper, a new auxiliary teeth structure has been proposed for fault-tolerant PM generators and the auxiliary teeth structure has been optimized to improve the fault-tolerant capability. The performances of fault-tolerant PM generators with different stator structures have been investigated. The results show that the auxiliary teeth structure has better fault-tolerant capability than the conventional two-layer windings. Firstly, the auxiliary teeth structure can reduce the short-circuit current. Secondly, phase to phase short-circuit fault can be completely avoided. Also, the phase to phase isolation can be reduced greatly. Moreover, the stator MMF harmonics can be suppressed by adopting the auxiliary teeth.
Furthermore, the cogging torque and torque ripple can be suppressed. Finally, the 10-pole/12-slot fault-tolerant PM generators have been designed and the simulated results have been given to validate the theoretical analysis. It has been verified that the proposed structure is effective to improve the fault-tolerant capability. The proposed design can provide a bright potential for fault-tolerant PM generators.

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