Design and Analysis of a Fault Tolerant Permanent Magnet Alternator for Aerospace

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Abstract -- In this paper, 28 slot-18 pole and 24 slot-20 pole permanent magnet alternators (PMA) with soft magnetic composite slot wedges are designed and compared. Power lane separation required due to fault tolerance requirements, means the proposed machines initially do not produce balanced phase voltage and currents, resulting in high ripple on the rectified power output. The alternators are optimised using 2-D finite element analysis (FEA) to get smoother DC power waveform. It is shown that the power ripple might be reduced by about 12% and un-balanced windings can be significantly balanced by thickening up the SMC slot wedges between the sub-machines. Furthermore, no load loss analysis has been conducted at rated speed and it is shown that 28s18p machine generates lower loss on no load condition compared to 24s20p single layer PMA.

Index Terms-- Alternator, aerospace, fault tolerance, finite element analysis, magnetic wedge, permanent magnet machine

I. INTRODUCTION

A dedicated fault tolerant power generation system is crucial for the engine control unit in aerospace applications, which is usually based on permanent magnet (PM) machines due to high power density, low volume and weight for a given torque rating compared to wound rotor designs [1]. The permanent magnet alternator (PMA) in an aerospace engine is directly driven from the engine gearbox via a dedicated low speed output to provide constant power across a wide engine speed range [2-3]. The low speed power requirement drives the magnetic design and slot wedges are used to increase the inductance and limit current and power output at high speeds.

The principal reason for a dedicated generator as part of the engine control electronics suite is due to the prevent loss of aircraft power causing a thrust control failure on a large civil aircraft. The engine control suite, however needs to be powered from an uninterruptable source. For this reason, fault tolerant permanent magnet alternators are an important part of aero-engine control units.

The adoption of fractional slot concentrated windings in PM machines enables electric, magnetic and thermal separation so that distributed windings can be avoided in such fault tolerant designs. Recently, non-overlapping single tooth windings are considered as high reliability solution for aerospace as they can inhibit short circuit current [4] yet high

magneto motive force (MMF) and large slot openings are disadvantageous due to high induced eddy-current losses in rotating parts of the machine [5-6].

In this paper, two fault tolerant PM alternators having the same volume envelope have been designed using FEA. A detailed comparison of the characteristics of the surface PM machines with soft magnetic composite (SMC) magnetic slot wedges is presented. Soft magnetic composites, which consist of iron powder particles coated with insulation can provide 3-dimensional magnetic flux paths [7]. Although SMC usually has a lower relative magnetic permeability in comparison to conventional electric steels, they are well suited to couple machine parts magnetically, provide relatively easy manufacturing [8] and provide a great freedom in terms of geometric shape. High permeability SMC magnetic wedges hence might be useful in the design of fault tolerant PMAs in order to limit short circuit currents.

The proposed machines will have four star connected, 3-phase independent outputs implying that the complete machine must allow galvanically isolated sub-machines within the given volume. Since aero-engine systems usually impose well defined dimensional constraints for the machine integration, Table I shows the maximum available length and diameter for the PMA design along with the other design constraints.

TABLE I. KEY SPECIFICATIONS OF THE PMA

Stator outer diameter	190 mm
Stack length	30 mm
Line to line RMS back EMF at 15000 rpm	230 V
Power delivered from each sub-machine at 400 rpm	40 Watts
The maximum short circuit current at 15000 rpm – per phase	20 A_{rms}
Speed range	0 - 15000 rpm
Insulation system life expectancy	300,000 Hr

As tabulated in Table I, there are two design points. Firstly, the output power of the each sub-machines must be at least 40 Watts at low speed: 400 rpm. Secondly, the PMA must be fault tolerant and the maximum short circuit current flowing from

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any pin on the machine shall not exceed $20 A_{rms}$ at 15000 rpm, rated speed. The peak phase back EMFs are also limited and they shall not exceed 187.8 Volts at rated speed. The PMA spends much of the time at short circuit to limit the output power [3]. Therefore, high speed losses might be of importance in the machine.

The requirement for high inductance necessitates small slot openings or the use of magnetic wedges [9]. This complicates the fabrication process yet the proposed PMA utilises magnetic wedges to form a fluid tight seal to the stator.

As an SMC slot wedge material, Somaloy 700 HR 3P (by Höganäs) was chosen which provides high mechanical strength (Young's modulus = 170 GPa) and it has a relatively high magnetic permeability: $\mu_{max} = 770$.

Fig. 1. B/H curves for Somaloy 700HR 3p and NO18 silicon steel

As given in Fig. 1, the SMC wedge material saturates at lower magnetic field (≈ 1.1 T) compared to the laminated stator and rotor cores of the PMA. The SMC as a wedge material needs to be magnetically less permeable than silicon steels yet it should be much more permeable than air to increase phase inductance. High leakage flux at the slot opening will decrease the machine power density. For a fault tolerant design, it is however necessary to increase the slot leakage inductance as it is an important parameter to restrain short circuit current, which is a function of phase reactance, at high speeds.

Furthermore, magnetic wedges are worth investigation as they can reduce cogging torque [10] and magnetic field variation, thus reducing induced asynchronous spatial harmonics in the airgap due to large slot openings. Therefore, this work aims to optimise the slot shape and magnetic wedge thickness of the proposed permanent magnet alternators to achieve high power density along with preserving the machine fault tolerance.

II. THE PRINCIPALS OF SLOT LEAKAGE INDUCTANCE IN A FAULT TOLERANT MACHINE DESIGN

To make the PMA work well under no-load short circuit fault condition, a phase inductance design approach by altering the machine slot leakage inductance, dependent upon the SMC slot wedge dimensions has been proposed.

A. Fault Tolerant Design

The phase inductance, L of the PMA consists of the synchronous inductance L_s , the harmonic leakage inductance L_h , the end leakage inductance L_e and the slot leakage

inductance L_{slot} . At higher speeds when the phase resistance $R \ll \omega L$, the short circuit current I_s can be written as given in (1) [11]:

$$I_s \approx \frac{E}{\omega L} \quad (1)$$

where E is back EMF and ω is the electrical angular frequency. Similarly, the slot leakage inductance L_{slot} must be in the form:

$$I_s < \frac{E}{\omega L_{slot}} \quad (2)$$

The magnetic SMC wedges in the slot openings control the machine inductance and it is a design optimisation parameter that can be optimised to achieve about 1 p.u. inductance, which makes the machine fault tolerant under given specifications.

Fig. 2. Slot leakage inductance when a magnetic wedge exists in the slot openings

In Fig. 2, the slot leakage flux is depicted where the magnetic field crossing the slot in the y -direction is called the slot leakage inductance. Using the co-energy and inductance relationship, per-slot leakage inductance can be written as given in (3) when SMC wedges exist in the tooth tip area and assuming no tapered area in the slot openings.

$$L_{sper-slot} = N^2 \left[\frac{\mu_0 d_s L_{st}}{3 w_{sb}} + \frac{\mu_0 \mu_{rSMC} d_{sh} L_{st}}{w_{so}} \right] \quad (3)$$

The physical dimensions are shown in Fig. 2 and μ_{rSMC} given in (3) is relative magnetic permeability of the SMC wedge of Somaloy 700HR 3p. The first term given in (3) considers the effective permeance of the coil is one-third of the normal permeance of the slot due to winding occupation. The second term takes the SMC permeability into account. With the SMC wedge design, the desired fault tolerance can be obtained as the machine slot leakage inductance can be altered by SMC wedge dimensions: d_{sh} and w_{so} for the given stack length L_{st} in Table I.

III. 28 SLOT – 18 POLE DOUBLE LAYER WINDING PERMANENT MAGNET ALTERNATOR

The fault tolerant PMA design requires four separate three phase power lanes and each lane should be physically isolated

from the others. The four spacer teeth enables physical isolation between the lanes and leave 24 slots for the machine windings. 90° electrical separation between the lanes has been achieved by the spacer teeth and the 16 rotor poles out of 18 poles cover the machine power lanes.

The machine winding configuration was arranged such that the diametrically opposite channels are electrically in phase with each other. A sub-machine winding configuration is shown in Fig. 3 below.

Fig. 3. PMA Winding configuration for a single channel

Due to the physical separation of the power lanes, as required for fault tolerance, the winding configuration for the proposed PMA becomes inherently un-balanced as the phase windings were not physically distributed equally around the stator circumference.

A. FEA Design of 28 slot – 18 pole PMA

The FEA model of the double layer winding PMA is illustrated in Fig. 4. The machine utilises thermally stable Samarium Cobalt PMs with a residual flux density B_r of 1.04 T at 20°C and the air gap length was set to 1.5 mm regarding mechanical reliability of the machine.

Fig. 4. 28 slot - 18 pole PMA model

After initial dimensioning of the PMA, the magnet shapes are optimized to reduce back EMF harmonics by using a parametric FEA model. The magnet pole pitch was set to 171° electrical after optimisation of magnet upper corners as given in Fig. 5 to get higher back EMF at the end. The magnet shape optimisation reduced 5th, 7th and higher order harmonic significantly.

Fig. 5. Magnet shape optimisation - parallel magnetisation

Fig. 6. PMA sub-machine voltage waveforms on no load at 400 rpm

Both back EMF harmonics and cogging torque contribute to output power ripple. In Fig. 6, the back EMF waveforms are obtained when the 1.5 mm flat magnetic wedges are in place and the stator teeth, rotor inner/outer diameter and slot wedge dimensions were later optimized to meet the fault tolerance which is a function of stator slot and wedge dimensions. The total harmonic distortion (THD) of the back EMF for the chosen magnet shape is 5.22% which was initially 11.16%.

B. The Effect of Slot Wedges on the PMA Power Output

The effect of magnetic SMC wedges on the alternator cogging torque, back EMF, power output and fault tolerance is significant. While the thinner SMC wedges usually increases back EMF and alternator power, the thicker wedges reduce short circuit current due to increased slot leakage inductance. Therefore, the dimensions of the SMC is an optimisation parameter to achieve power requirement at low speed: 400 rpm and short circuit restriction at rated speed: 15000 rpm. The output power quality is investigated when the alternator is connected to a 3-phase full wave diode rectifier cascaded with a constant DC voltage source as shown in Fig. 7. The output power and power ripple are investigated when the rectifier circuit is present in the FEA.

Fig. 7. A three phase sub-machine connected with a DC full wave rectifier

Initially, the wedge thickness is varied between 0.5 mm and 2.5 mm to see the DC power at the output, as given in Table II. As the PMA must satisfy 40 Watts power per channel, the wedge thickness above 2 mm does not satisfy the specification. Also, the thinner the wedge thickness the greater the output power ripple. The wedge thickness is optimised to achieve about 1 p.u. inductance to reduce short circuit current. The mechanical limitation on the minimum SMC wedge thickness is an important design consideration that can be overcome by choosing an SMC material with lower relative permeability as this would allow to thicken up the magnetic wedges by keeping the amount of the slot leakage flux through the wedges the same.

TABLE II. WEDGE THICKNESS VS. DC OUTPUT POWER

Wedge Thickness (mm)	DC Power (W)	Power Ripple (%)
0.5	109.68	19.16
0.75	97.59	21.97
1	83.5	24.31
1.5	59.86	33.13
2	37.97	44.91
2.5	22.45	64.26

The short circuit current are greatly reduced when the SMC wedges of 1.5 mm are in place. The rms short circuit current at steady state when SMC wedges are present is $19.9A_{rms}$ while it is $43.52A_{rms}$ for the PMA with open slots. The transient short circuit response at rated speed on no load condition is compared in Fig. 8 with and without magnetic wedges.

Fig. 8. PMA Phase B short circuit current transients on no load

Fig. 9 also demonstrates the cogging torque reduction for the PMA with and without wedges. More than 10 fold peak to peak cogging torque reduction was obtained for the PMA with 1.5 mm SMC wedges.

Fig. 9. Cogging torque in 28 slot – 18 pole PMA with and without wedges

C. Un-Balanced Alternator Currents

In Table II, it can be noted that the percent DC power ripple in Y-connected PMA output is around 33% for 1.5 mm wedge thickness. This states that the PMA sub-machines generate un-balanced voltage and current waveforms due to phase inductance differences between the machine phases. Due to the existence of spacer teeth, each sub-machine experiences an end effect implying that the side phases (i.e. Phases A & C) have less inductance whereas the middle phase (B) has higher inductance due to a higher mutual inductance. Therefore, the proposed 28 slot – 18 pole PMA will not have a perfectly balanced configuration.

Fig. 10. Y-connected sub-alternator phase currents - unbalanced

Fig. 10 shows the un-balanced phase currents when the Y-connected sub-PMA is coupled to a rectifier circuit. In this case, Phase B gives about 27.5% less current and it has higher inductance. In order to balance a machine with inherently un-balanced winding configuration, a set of methods has been proposed in this work. This in turn results in smoother output DC power in the proposed double layer PMA.

D. Method 1 – Wedge Thickness in Spacer Teeth

In the first method, the SMC wedges in the spacer teeth slot openings have been thickened to increase slot leakage inductance of the end phases which are Phase A and Phase C for the double layer PMA. All other magnetic wedges are left as they are. The thicker the wedges in the spacer teeth, the higher the self-inductance of the side phases of a sub-machine.

Fig. 11. End effect in sub-alternators

As given in Fig. 11, the spacer tooth thickness ($t_{toothSp}$) and the spacer tooth wedge thickness (t_{wSp}) are two important parameters to vary slot leakage of the end phases shown in Fig. 11. The effect of ($t_{toothSp}$) on the DC output power magnitude and ripple is investigated in Table III below.

TABLE III. EFFECT OF SPACER TOOTH THICKNESS AT THE OUPUT POWER

$(t_{toothSp})$ (mm)	3	5	6	7	8	9	9.4
Power ripple (%)	33.1	35.1	34.4	36.6	38.2	41	41.5
Output Power (W)	59.8	59.2	57.8	56.1	54.7	53.9	53

As tabulated in Table III, the DC output power is linked with physical dimensions of the spacer tooth as it is not only a physical separation between the sub-machines but it varies the slot leakage inductance of the end phases. Similarly, the effect of spacer tooth wedge thickness on the output power is examined in Fig. 12 when $t_{toothSp}$ is 3 mm.

Fig. 12. Power ripple for different spacer tooth wedge thickness

As shown in Fig. 12, the power ripple on the constant DC link is reduced to 20.87% and the sub-machine achieves the minimum power requirement. This leads to more balanced current waveforms in the Y-connected alternator as depicted in Fig. 13.

Fig. 13. Y-connected sub-alternator phase currents - more balanced

E. Method 2 – Magnetic Wedge Selection in the Middle Slot of a Sub-Machine

The SMC magnetic wedge coupling only Phases A and C, as shown in Fig. 14, can be adjusted to give more balanced current waveforms. Firstly, a number of materials with different relative permeability have been investigated, as illustrated in Fig. 15. Secondly, the optimum wedge thickness was found. In this case, 1.5 mm wedge thickness achieves the lowest ripple (26.6%), when the relative permeability, $\mu_{r_{max}}$ of the material is 1000.

Fig. 14. The middle magnetic wedge coupling Phase A & C

When $\mu_{r_{max}}$ is low and the material saturates at a lower flux density, the output power ripple will be significant, up to 49%. Fig. 15 proves that the magnetic wedge linking end phases in the middle is an important optimisation parameter to achieve smoother power at the output.

Fig. 15. Rectified power output of a sub-PMA and ripple percent

IV. 24 SLOT – 20 POLE SINGLE LAYER WINDING PERMANENT MAGNET ALTERNATOR

An alternative configuration is shown in Fig. 16, utilizing single layer windings and thinner spacer teeth between individual coils. The machine does not suffer from un-balanced current and voltage waveforms significantly as the mutual inductance ($7\mu\text{H}$) coupling between the coils is very low.

Fig. 16. 24 slot - 20 pole PMA model -half

2-D FEA optimisation has been performed to reduce power ripple at the rectifier output. The results are plotted in Fig.17 to choose the optimum machine dimensions.

Fig. 17. (a), (b), (c), (d), (e) – FEA optimisation of the PMA to obtain smoother power output in each sub-machine; (f) Sub-machine back EMF at 400 rpm; (g) Highly balanced Y -connected sub-alternator phase currents; (h) Short circuit current transients at 15000 rpm

24 slot – 20 pole single layer PMA gives about 19.8% power ripple and achieves 73.9 Watts power at low speed: 400 rpm. The short circuit currents on no-load condition is $19.7A_{rms}$ meets the short circuit criterion at rated speed. The key machine dimensions and features are given in Table IV.

TABLE IV. 24 SLOT- 20 POLE PMA KEY PARAMETERS

Tooth thickness	5 mm
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Spacer (Thin) Tooth thickness	4 mm
Slot opening	12.985 mm
Stator core back thickness	7 mm
Air gap length	0.864 mm
Inconel 718 sleeve thickness	0.636 mm
SMC wedge thickness	1.5 mm
Magnet thickness	8.6 mm

Rotor inner diameter	80 mm
Rotor outer diameter	128 mm
Stator outer diameter	190 mm
Bare slot area	330 mm ²
Number of turns	58
Stack length	30 mm

V. NO - LOAD PMA LOSS ANALYSIS AND COMPARISON

Rotor eddy current losses due to space (MMF) harmonics can be significant if a fractional slot concentrated winding in single layer winding configuration is chosen [12]. Single layer windings inherently produce more spatial harmonics compared to double layer windings implying higher rotor losses. In order to understand rotor losses in the proposed single and double layer PMAs, tangential H field (H_t) harmonics across the stator bore can be investigated. In Fig. 18, spatial MMF harmonics for the double layer and single layer PMAs are shown.

Fig. 18. Spatial MMF harmonics for: (a) 28s18p PMA, (b) 24s20p PMA

Due to rich air gap spatial harmonic content of single layer 24 slot – 20 pole PMA, it is expected that this configuration leads to higher rotor core losses. Nonetheless, double layer 28 slot -18 pole PMA eliminates sub and super harmonics significantly and gives notably less rotor core losses as depicted in Fig. 19 below. Although the 28 slot – 18 pole machine employs inherently un-balanced winding

configuration, this negative effect was greatly reduced by the approaches discussed previously.

Fig. 19. PMAs loss comparison on no load condition at rated speed

It should be noted the efficiency merits of the PMAs are not of concern as the proposed machines do not target any specified power output at high speeds. The design optimisation considers a power requirement at low speeds only. The rated speed losses as shown in Fig. 19 would not be a problem in the final design as the machine will utilise flooded rotor and stator, which will improve the thermal performance of the machine significantly.

VI. CONCLUSION

In this paper, single layer 28s18p and double layer 24s20p PMAs utilising SMC slot wedges have been proposed for an aerospace alternator. The PMAs have been optimized using 2D-FEA to get smoother power at the rectified output. The effect of SMC slot wedges on the balance of phase windings have also been described. It is shown that the proposed PMAs achieves similar power ripple (i.e. about 20%) and satisfy all fault tolerance requirements yet single layer 24s20p machine produces significantly high rotor losses at rated speed. Due to strict fault tolerance requirements, the power ripple at the output of the PMAs is relatively high. The principal cause of the high power ripple is that the winding layout in the proposed machines form four sub-machines next to each other, implying that the winding layouts are not conventional. In terms of the machine performance, 28s18p PMA, however, becomes a better option.

VII. REFERENCES

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VIII. BIOGRAPHIES

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