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Design and performance of a Segmented Stator Permanent Magnet Alternator for Aerospace

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Abstract

Reliable performance is of primary importance when designing machines for aerospace applications. In the case of generators, it forces thermal, electrical and physical isolation of phases and imposes a limit on short circuit current. Single tooth high inductance permanent magnet machines suit the application and have been in use for many years. However, the small slot clearance forces the use of labour intensive manual winding techniques. In this paper, we present the redesign of an aerospace permanent magnet alternator to a segmented stator design, including alternative topology options, design procedure and results. Segmentation is shown to improve the production process and improve copper fill factor but in the first prototype appears to adversely affect material properties.

1 Introduction

The Permanent Magnet Alternator (PMA) in an aerospace engine provides a redundant power supply to the Full Authority Digital Engine Control (FADEC) engine control electronics and actuators; the PMA is powered from the engine gearbox, via a dedicated low speed output and must provide constant power across a wide speed range. The power is regulated by the FADEC to a defined output voltage using a fixed frequency PWM shunt regulator but for test purposes a passive rectifier arrangement as per Figure 1 will be used. The machine requires a very high per unit inductance to limit the short circuit current to acceptable values at full speed (14,000rpm). It is rated and sized for the low speed (6% of rated) performance requirements, corresponding to a windmilling start. It is thus heavily over rated at its rated speed performance specification. 100% speed open and short circuit losses are therefore critical to prevent overheating.

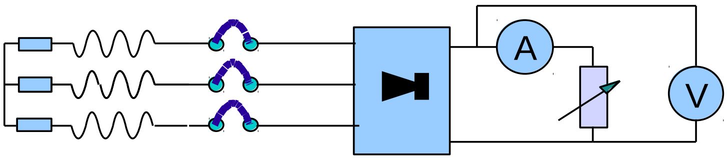

Figure 1: Passive rectifier and DC link

The present stator design is a conventional single lamination semi-closed slot design with steel slot wedges for mechanical security of the coils and manually altering the machine inductance for different requirements via deliberate slot leakage – Figure 2.

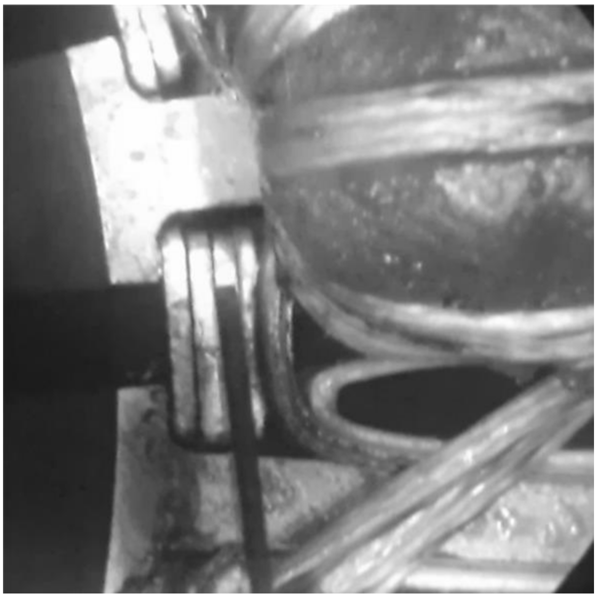

Figure 2: Photograph of incumbent slot wedge design

2 Design Options

The requirement for high inductance necessitates small slot openings and/or the use of magnetic wedges. This complicates the fabrication process and the wedges are believed to be a significant source of loss from eddy currents due to their solid magnetically permeable nature

In the present process, Silicon Iron laminations are pressed externally from sheet metal. They are cleaned (acetone) then dried. The stack is made up, with end the laminations being of a thicker width as the internal lamination sheets are quite fragile. Care has to be taken when arranging the stack that all the laminations are orientated facing the same way due to the burrs created during the stamping process. When the stack has been built to the correct dimensions the rotation of the individual laminations is randomised by a manual process. Adhesive impregnation under vacuum takes place after the laminations have been cleaned, and stacked. Nomex paper is then manually inserted into the slot to act as an electrical isolator.

Each coil consists of three parallel windings, which improves fill factor, allows a tighter end winding bend radius and, crucially, eases insertion through the small gap between adjacent teeth. Coils are wound on a former and then manually fanned out and inserted between teeth into the slots. Slot wedges are slid above the coils to give mechanical rigidity and increase inductance. The coil groups for each power lane are physically separated in the machine, however their terminating cables do overlap, requiring additional isolation to be placed in the end winding region.

Three alternative techniques were considered with a view to automating the process and specifically removing the need for slot wedges.

2.1 Reduced slot opening

The magnetic function of the slot wedges can be replaced by closing the stator slot opening, Figure 3. The stator teeth are made from laminations spanning the full 360 degrees, with the coils single tooth wound directly onto the electrical machine.

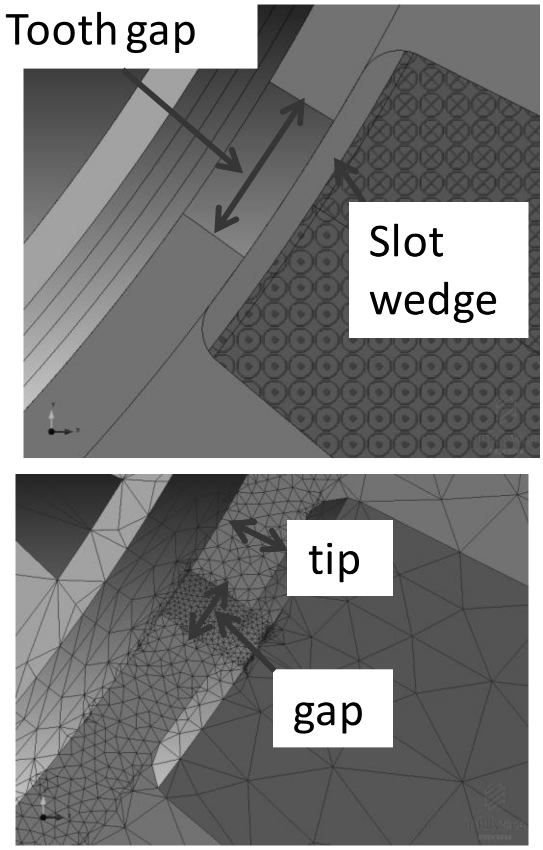

Figure 3: Slot wedge (upper) verses re-shaped tooth (lower) for equivalent magnetic performance

Reduced physical gap between adjacent teeth exacerbates the need for manual intervention during winding by preventing the use of needle winding.

2.2 Fully closed slot

In a closed slot stator, individual teeth are joined on the inner radius, Figure 4. In a conventional layout, a lack of radial access to the slot would require manual winding. In this scheme it was proposed to split the stator into two components: a set of teeth joined at the inner radius and the stator coreback - consisting of a removable outer ring. Pre wound coils could be slotted over teeth from the outer radius prior to slotting the entire coil set into the back iron.

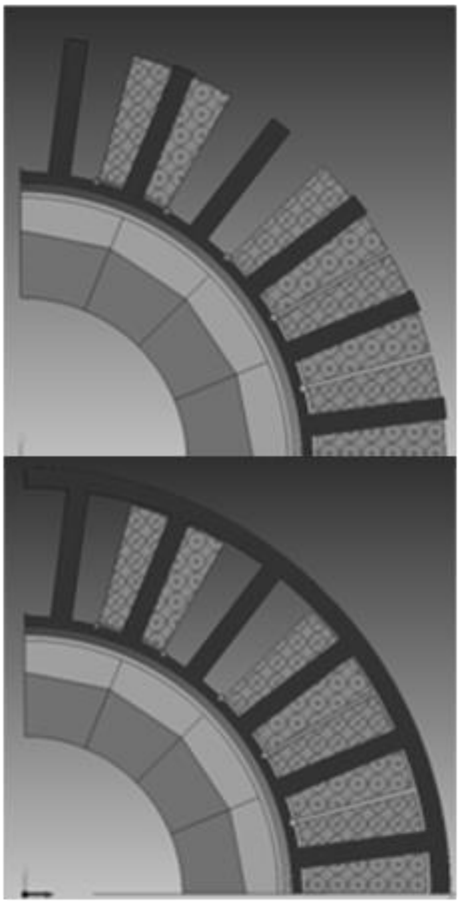

Figure 4: Fully closed slot design. Before (upper) and after (lower) back iron slotted over machine

2.3 Segmented stator

The segmented stator design involves building the machine from single segments each consisting of one tooth, Figure 5, and one coil. Segments are interlocked together by mechanical features and held in place via a compression ring.

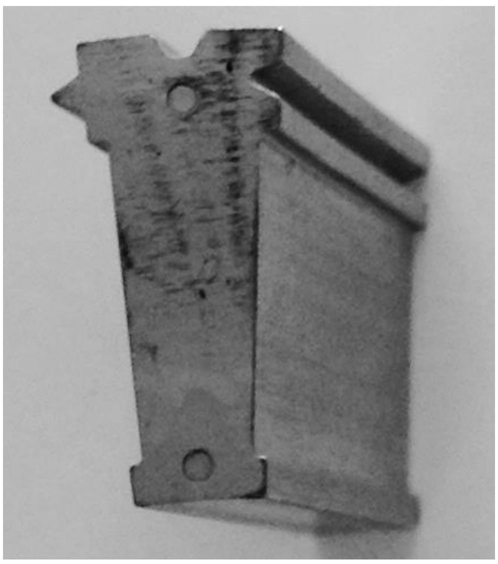

Figure 5: Single segmented stator tooth

After consideration of the entire production process, with a particular emphasis on automated coil winding, this concept was selected to be taken forward as the one to deliver the most saving in production time and cost. Benefits of the segmented stator are high copper fill, small end windings and a more reliable manufacturing process. Work elsewhere has discussed the benefits of this approach, the impact on thermal modelling [1] and the effects of airgaps between adjacent segments [2].

3 Slot Pole Combination

The design requires four separate three phase power lanes, defined as the ‘main’ and safety power lanes for channels A and B. Each lane should be physically isolated from the others and there was a requirement for balanced short circuit current across the lanes. Single tooth windings are known to create high spacial harmonics in the air gap magnetic field, so selection of the rotor pole / stator slot combination is critical to the anticipated rotor loss. After investigating various combinations, an 18 pole rotor was selected. The four spacer teeth each covered 90^0 electrical between power lanes, totalling 360^0 and leaving 16 poles for the power teeth. The four rotor poles per channel correspond to six 120^0 teeth. The stator therefore has 28 teeth, as shown in Figure 6.

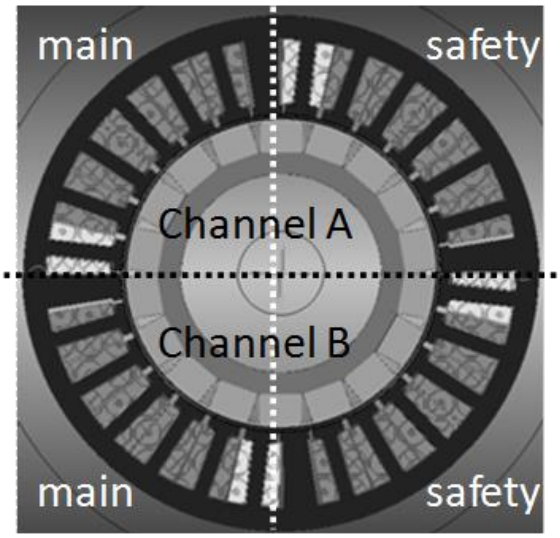

Figure 6: Coil layout of entire machine

4 Electromagnetic design of the segmented stator

4.1 Tooth tip

The design process for the PMA focuses on achieving the required back EMF to deliver the low speed power performance, then tuning the inductance to limit the short circuit current at high speed. Reducing current density given a fixed short circuit current requirement tends to require a reduction in turns and a longer machine, as the OD of the stator is fixed. Inductance will be driven by the stator stack length, whereas magnet flux is driven by axial length of magnet. The influence of tip geometry on predicted machine inductance, as calculated by 3D FEA, is shown in Figure 7, using notation defined in Figure 3.

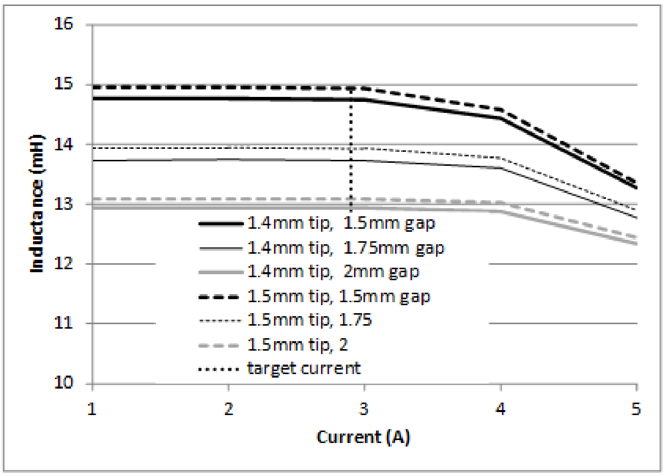

Figure 7: Finite element analysis predictions of inductance variation with current for alternative tooth tip configurations

4.2 Material

The project was advised that the lowest practical thickness of nickel iron is 0.2mm but this could only be used in traditional round stator stacks and would need bonding or laser welding. For individual interlocking T-sections, designers were advised that to avoid the issues with bonding and laser welding we should be looking at laminations of a minimum thickness of 0.35mm. This lamination thickness is greater than would normally be used but adequately low losses should be possible if correctly heat treated nickel or cobalt iron is used.

In retrospect, results show this advice was flawed, as the introduction of an exotic material, sensitive to manufacturing processes, is believed to have adversely affected by the machining and pre-tensing required for this assembly.

5 PMA Prototype

Based on the method and discussion above, a segmented stator was designed, fabricated (Figure 8) and inserted into the existing machine casing.

The prototype was tested on a constant speed test rig (Figure 9), where shaft speed, torque and casing temperature were measured.

Figure 8: Final stator during assembly, prior to inserting in machine casing

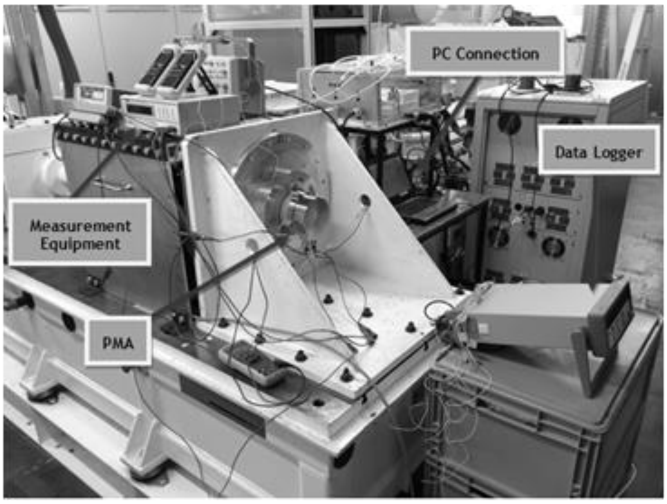

Figure 9: Machine mounted on test-bed

Measured open circuit voltage at 50% speed is shown in Figure 10, where a 7% rms over prediction is apparent. The low speed power delivered into a variable load bank by a bridge rectifier connected to two single power lanes is shown in Figure 11 – showing a variation of 5% at higher voltages between lanes.

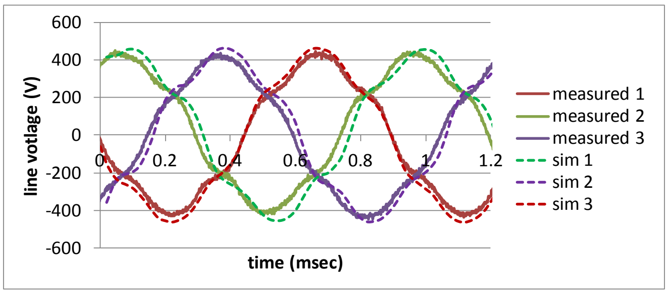

Figure 10: 50% Speed open circuit back emf results

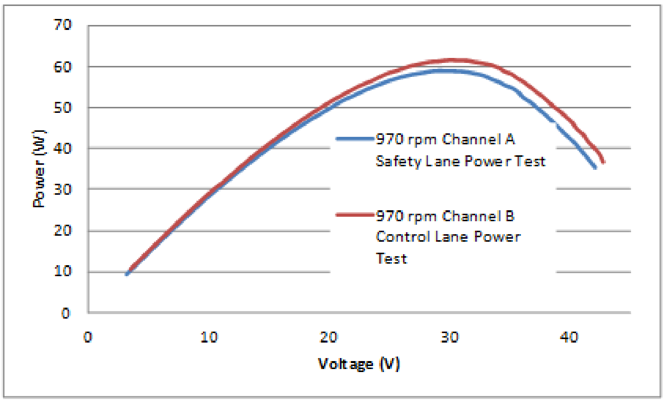

Figure 11: Power from the DC bus for diametrically opposite power lanes

From this selection of results, the electromagnetic model can be assumed to be accurate and consistency between phases is acceptable although neither is perfect.

6 Iron Losses

During 100% speed tests, the PMA became hotter than anticipated and two methods were used to independently predict the iron loss.

6.1 Experimental loss prediction based on temperature

Temperature was measured during a 100% speed 90 minutes open circuit test. The temperature of the mounting plate is shown in the solid black line of Figure 12. The test was repeated with the rotor in air by removing the stator housing – the no-stator test - where rise in temperature was assumed to be due to bearing loss alone (dotted line Figure 12). To provide a relationship between temperature rise and total loss, known DC currents were applied across all power coil lanes (grey lines Figure 12). By linear extrapolation, Figure 13, the implied iron loss (open circuit temperature rise minus the no-stator temperature loss) can be deduced to be approximately 420W during the open circuit test.

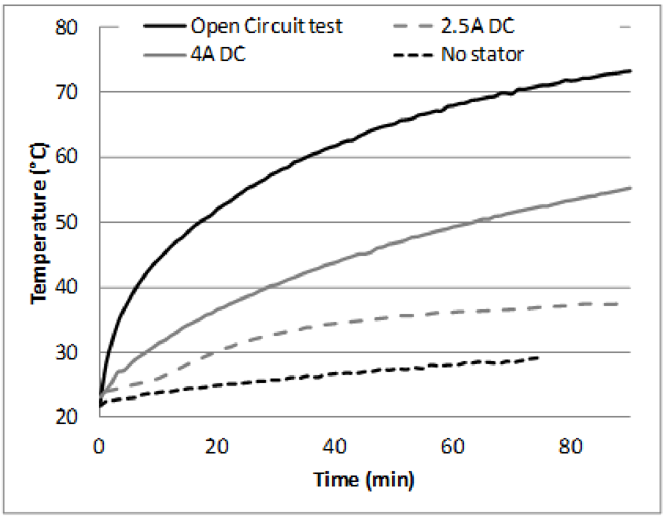

Figure 12: Base plate temperature variation with time for 100% speed open circuit test and static DC test for reference

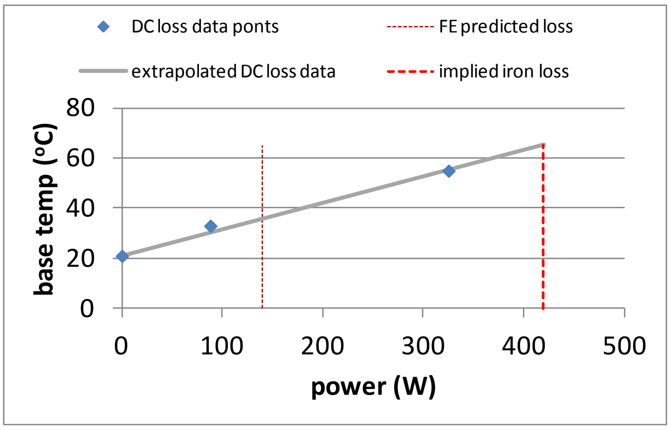

Figure 13: Relating base temperature rise of 90 mins to power loss

6.2 Experimental loss prediction based on mechanical power

Mechanical power into the rig was measured during the 100% speed open circuit and no stator tests. The windage loss was estimated to be 8W using an empirical formula relating the drag force to machine geometry and speed, assuming the rotor is a smooth cylinder with flat ends[3]. The total windage consists of a torque coefficient from the cylindrical surface and a second coefficient from the end surfaces of the rotor – the 'end effect'. The end effect is independent of the presence of the stator.

The windage loss for the no-stator test was estimated by setting the machine air gap to 1m in the empirical formula [3]; calculated windage loss is larger in the open air test than with the rotor within the stator, (12W verses 8W). As the measured mechanical power was an order of magnitude larger than both these values, the effect of the presence of the stator on windage loss is negligible and will here be ignored. No attempt has been made to estimate the bearing loss analytically. The total windage and bearing loss during open circuit testing is thus assumed to be equal to that measured during the no-stator test.

The total mechanical power at 100% speed during open circuit tests was 580W, of which the measured windage and bearing losses account for 135W. The implied iron loss from mechanical power is therefore 580-135=445W.

6.3 Steinmetz loss prediction

Core losses are generated on a microscopic scale within a material, whereas core loss prediction uses a macroscopic scale based on assumptions such as magnetic field uniformity. Therefore, the accuracy of core loss predictions is dependent on how well macroscopic properties model the material loss properties. Different types of core materials have been investigated considering frequency and peak magnetic flux density dependent iron losses (eddy + hysteresis). In the finite element analysis, material core losses are predicted using Steinmetz equation, which relates experimentally measured loss per kg of a sample of material to frequency, flux density and material constants.

Seven alternative materials were simulated using a transient 3D finite element analysis solver to generate a range of loss predictions at 100% speed open circuit. Values ranged from 88W for Magnifier 50 to 480W for M270-50A. It is interesting to note that the actual behaviour of the PMA is most aligned with the predictions given by general electrical steel M270-50A.

Although comprehensive modelling data was not available for the actual material used, lowest iron loss result was obtained using materials close to the material used in the prototype laminations. Work continues to validate this result.

6.4 Discussion of Losses

The two experimental figures for iron loss at 100% speed (445W and 420W) broadly agree with each other, and are over four times higher than the predicted iron loss using the expected material properties. Iron loss prediction is therefore inaccurate. The FEA software calculates iron loss by a statistical approximation and extrapolation of loss measured as a function of frequency(Hz) and flux density (T).

One source of error is that the material data used by the software is inadequate, not covering a high enough flux density / frequency. In addition, the effect of lamination processing on material properties is not considered. Specifically, it is likely that the loss in the tooth tips - where flux density is the highest and material processing effects most significant compared to the area - is being underestimated. It is extremely likely that the processing of the lamination material to allow for a segmented stator has damaged the magnetic properties and account for this increased loss figure. This is an area of continued investigation.

7 Conclusion

A segmented stator design has been presented for a permanent magnet alternator which requires a large inductance. Segmentation was driven by the desire to improve winding reliability, and reduce assembly time, which was successfully achieved. The material choice was governed by the need for 0.35mm laminations to allow interlocking to be performed, as advised by the supplier. Iron loss was measured using two methods for open circuit 100% speed operation. Both methods give loss values over four times that predicted in the software model. The conclusion must be that the process of segmentation has damaged the loss properties of the iron. Further design work should focus on reduction of stator iron loss through the use of conventional silicon steels of thinner section (0.1-0.2mm) and identifying a reliable and cost effective method for bonding them in small stacks.

Acknowledgements

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