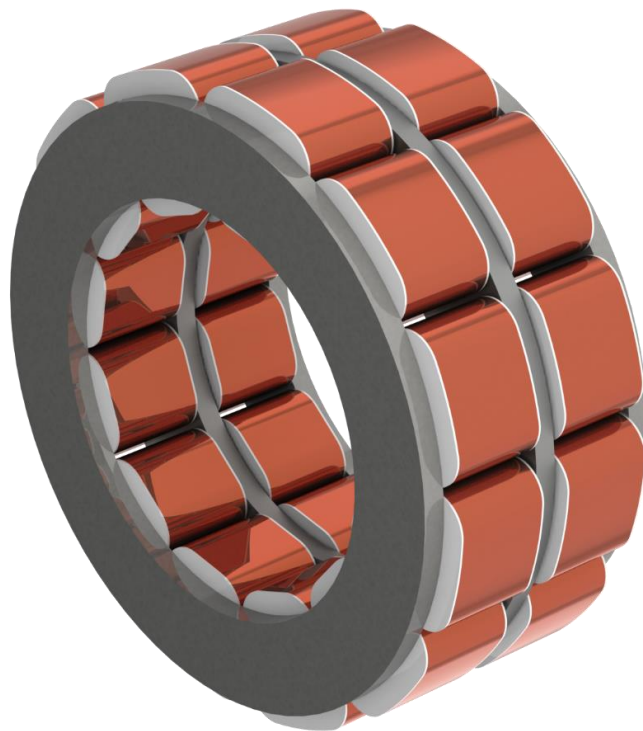


Soft Magnetic Composite Application Examples

Double-Sided Axial Flux Machines

October 2022



Abstract

The past decade has seen significant development in the field of soft magnetic composite (SMC) materials and their application in electrical machines. A large part of this can be attributed to their isotropic magnetic properties, allowing for relatively complex structures to support magnetic flux whilst suppressing losses. Furthermore, the material isotropy benefits the thermal performance, allowing heat to dissipate in all directions.

In order to take full advantage of SMC technology in electric motor applications, it is necessary to address the design, material and processing aspects. Radial flux motors are well suited to the axial symmetry that is fulfilled by laminated stacks of electrical steel sheets. Axial flux motors, however, are tricky to manufacture with this approach and provide a good design example for the SMC technology. The stator manufacturing benefits from the well-established powder metallurgical (PM) compaction process, a single operation that provides a final high density, net-shaped product. Subsequent heat-treatment relaxes the domains of the material and provides mechanical strength and a low loss characteristic.

This document presents a short overview of the SMC technology, from process to powder properties, together with a concept application study. The motor concept is an open-slot, double-sided axial flux machine (DSAFM) with 12 slots and 10 poles, designed to achieve a nominal specification. This concept has been modelled and simulated using JMAG, applying materials manufactured by Höganäs AB that are readily available in the JMAG material database. Details of the electromagnetic design process, model set-up and results are presented.

For more information on Somaloy®, the Soft Magnetic Composite (SMC) materials from Höganäs AB, please visit www.hoganas.com.

For more information regarding SMC applications, please visit www.alviermechatronics.com

Contents

Abstract..... 1

Introduction 3

 Process overview..... 4

 Material overview 4

Double-sided axial flux machine overview 6

Design Outline 7

Geometric Dimensions 8

Model Simulation Setup and Results..... 10

 JMAG Model Settings 10

Simulation Results 14

 Continuous Operating Conditions 14

Demagnetisation..... 16

Conclusion 17

Introduction

Soft Magnetic Composite (SMC) components are produced by the well-established powder metallurgy process, where compaction of powdered iron can yield high density, net shaped components. Through a reduction in manufacturing yield losses and post-production operations, it is an efficient and cost-effective process. Furthermore, lower energy consumption by comparison to other production technologies can be realised. The SMC materials are suitable for large-scale mass production of components with accurate tolerances, smooth surfaces, no secondary operations and minimal material waste.

The primary characteristic of the SMC materials is its ability to allow the magnetic flux to flow in three dimensions: the individually inorganically coated iron particles create a magnetically and thermally isotropic path which can provide benefits through the inherent freedoms of design. Moreover, the iron particles can be sized for specific applications, allowing the suppression of iron losses as frequency increases: as the particle size reduces, the surface area for the coating provides a greater bulk resistivity, in the region of tens of thousands of micro-Ohm metres, significantly reducing eddy current losses.

Relating the forming of an SMC component to a stack of punched lamination steel sheets underlines the advantages for the SMC process. SMC is formed to a net-shape in a single operation, achievable at speeds of up to 20 components per minute, depending on the size, required density and geometric complexity of the component. The SMC component is a single part, where almost all the powder from the filling shoe forms the component. This can be compared to punched lamination sheets, where a large amount of scrap material is generated, and the individual laminate sheets must be carefully handled, stacked and bonded to form a final assembly in a secondary process. Furthermore, the SMC component can be designed with chamfer or rounded edges in a plane perpendicular to the magnetic flux vector. This may improve the form factor for the coil winding and reduce its weight, saving on high-cost parts.

The intrinsic material properties lead to differences in magnetic, thermal and mechanical properties. Therefore, simply replacing the existing laminated iron core in an electrical machine with an SMC material will typically result in a loss of performance with very small compensating benefits. A lower relative permeability results from coating individual grains, and the use of high purity iron yields higher hysteresis losses: the dominant loss mechanism at low frequencies, particularly when compared to laminated steel. To overcome this, and to take full advantage of the SMC material, it is recommended to design the electromagnetic components with consideration paid to the unique property profile, moving to a higher pole number to increase frequency, for example.

The concept presented here is a double-sided axial flux machine (DSAFM). It is a surface mounted permanent magnet motor with a modular construction concept. The fabrication of the SMC parts greatly benefits from this modular approach, where compaction of a relatively simple stator component - in single respective press operations - allows coils, with associated insulation, wound off-part, and magnets to be applied prior to assembly. High strength NdFeB magnets are used to provide a strong magnet MMF whilst the pole number is chosen to deliver a compact solution, driving the

frequency of operation higher and into a region of comparatively lower loss. The slot-pole combination is selected to provide low ripple characteristics for an open slot stator.

Process overview

The powder process involves the creation of a base powder mix, which includes all the necessary elements for producing a robust SMC component, compaction and, finally, heat-treatment.

The compaction process is depicted in Figure 1, where powder is fed into a die tool cavity before being compacted under high pressure to form the final net-shape component. This is then ejected from the tool and transferred to the heat-treatment. Heat-treatment is conducted under a strictly controlled temperature profile to evaporate compaction lubricants, relax grains boundaries and harden the structure. The furnace can have a specific environment, where gases present in the atmosphere improve the component performance.

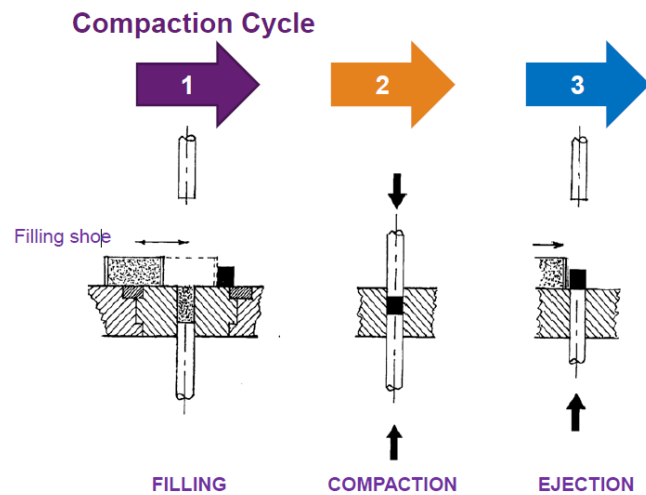


Figure 1. The PM Powder Metallurgy forming process in three steps

The component density is related to the actual pressure of compaction. The higher the component density the more magnetically active material is present. The performance of the material, in terms of loss, at a given frequency is determined by the size of the particles in the initial mix; for lower frequency applications, large particle sizes are best suited. Conversely, high frequency applications will benefit from smaller particle sizes, with an overall larger surface area available for coating. The properties and performance of the SMC material depends upon the powder mixes, discussed below.

Material overview

Höganäs AB Somaloy® is a family of SMC materials, which are made of high purity iron powders with nanometre-size inorganic surface insulation, as shown in Figure 2. The iron powders are available in several grades with particle sizes of between 50 – 250 micrometres. The Somaloy® family is grouped into performance levels based on the coating properties: 1P, 3P and 5P. The resultant performance of the powders is highly dependent on this coating and its sensitivity to the compaction and heat-treatment processes. The additives - such as lubricants for powder filling and ejection from the die tool post compaction, for example - and the heat-treatment process, must be optimal to yield the desired performance from the component.

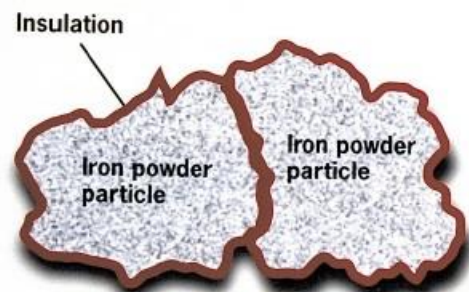


Figure 2. SMC powder particle with electrically resistive coating.

During the compaction phase, there is a physical limit on the pressure that should be applied to the powder in the die tool, which is determined by the pressing force and the part geometry. Under compaction forces that exceed the material limits, the coating will breakdown and the resultant component will not have the electromagnetic properties expected. Where heat-treatment is concerned, the maximum permissible temperature is important for fully stress relieving the grain boundaries after compaction has taken place. This will reduce hysteresis loss and improve permeability, through the removal of impurities, such as lubricants, for example. Exceeding this temperature will breakdown the coating and reduce the electromagnetic performance, along with introducing mechanical defects into the component.

The 1P material provides a base level of performance with a cost-efficient approach. A simple coating is applied, and the heat-treatment of the part is conducted in an air-atmosphere with a maximum temperature of approximately 500 °C.

The 3P grade uses a different additive to 1P to allow for a special steam-atmosphere during the heat-treatment. This brings maximal mechanical strength to the component by a forced oxidation deep into the material structure. The maximum temperature for the heat-treatment 3P is approximately 500 °C.

The most advanced SMC material grade is the 5P, which exhibits the lowest specific loss in the family. A special particle coating is designed to withstand heat-treatment temperatures up to 650 °C, resulting in a component with minimal residual stress post heat-treatment, and the lowest hysteresis losses available for current SMC products.

Double-sided axial flux machine overview

Both radial and double-sided axial flux machines share a similar electromagnetic arrangement, where magnet flux travels in the denoted direction: the two motor configurations are shown in Figure 3. It is clear that the flux path for a radial motor travels in a two-dimensional plane that can easily be repeated in the axial direction to form a laminated stack. For double-sided axial motors to utilise laminations, a complex index punching technique to create a spiral wound stack or the implementation of careful machining on a formed laminated ring would be required, creating a significant challenge for mass manufacture. SMC, therefore, becomes an ideal fit for motor topologies such as the double-sided axial flux machine, where the material's isotropic magnetic properties allow magnetic flux to flow in three dimensions whilst losses are suppressed in relation to the powder grain sizing.

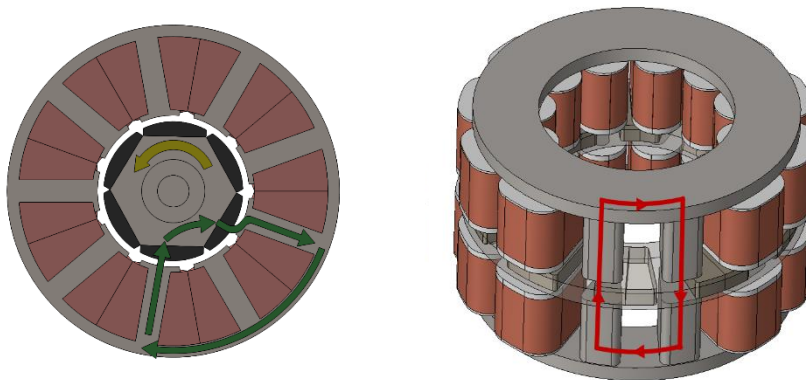


Figure 3: Flux path in traditional Radial Flux Machine (RFM) and Axial Flux Machine (AFM). The construction of a double-sided axial flux machine can be seen in Figure 4. Due to the nature of the compaction process, the two stators feature an open slot design. This allows coils to be wound separately onto bobbins and slotted onto the stator teeth. Additional tooth tips can be attached to the teeth in order to concentrate the flux and increase torque performance whilst further reducing cogging. However, this increases complexity and adds cost to the design with marginal benefits.

Opposed stators also help minimise axial forces that are a challenge with more conventional single-sided axial flux machines.

Magnets are encased the rotor frame. The rotor frame is made from nonmagnetic material to not interfere with flux flow between stators.

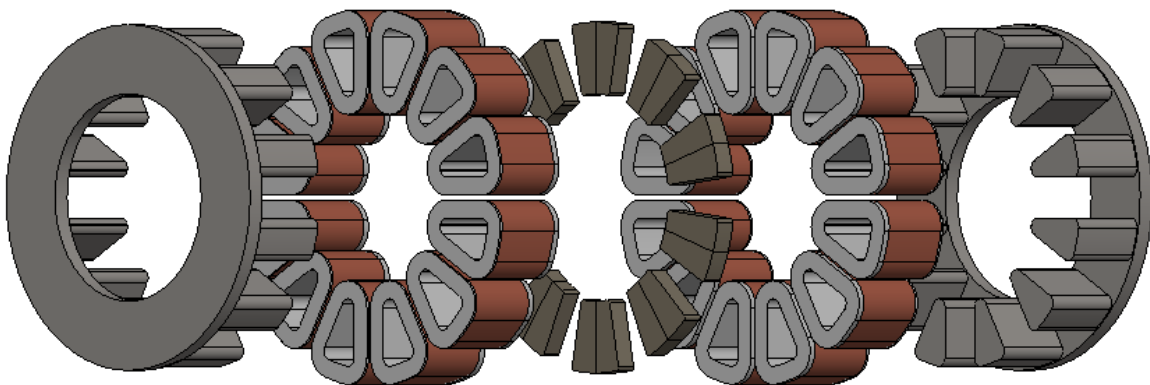


Figure 4. Double-Sided Axial Flux Machine components

Design Outline

This section describes the design approach for a DSAFM to fulfil a nominal specification. The stator SMC component is restricted to 100 mm outer diameter (OD) and the DC voltage fully available at the motor terminals is restricted to 350 V. The specification is displayed in Table 1. Since the machine is forced air cooled, the assumed continuous current density is restricted to a conservative 5 A_{RMS}/mm², where a short-term overload must also be achieved.

Table 1. Design Specifications

Parameter	Value	Unit
Peak power	7700	W
Overload torque	12.3	Nm
Nominal torque	5.1	Nm
Efficiency	92	%
Nominal speed	6000	rpm
Maximum speed	6000	rpm
DC voltage	350	V
Maximum OD (stator)	100	mm
Thermal management	Forced Air	-

Performance outlined in Table 1 is not possible to achieve with single-sided AFM with 100mm OD restriction. Double-sided AFM topology has to be used.

Geometric Dimensions

The suggested geometry for the design can be seen in Table 2, with key geometric parameters depicted in Figure 5. The stator component OD is 100 mm, however the additional winding width increases the total OD to 109.7 mm, with a total axial length of 66.2 mm. Magnet thickness of 6.2 mm is required to avoid demagnetisation. The magnet material is NdFeB, grade N45SH. The airgap is set to 1 mm on both sides, a clearance that can easily be achieved with regular production tolerances. The distance from the top turn of the coil to the airgap is set to minimise the effects of the parasitic AC copper losses.

The slot-pole combination, 12 stator teeth and 10 rotor poles, is well suited to an open-slot concentrated winding motor. The cogging torque is determined by the lowest common multiple of the slot-pole, where a greater number yields a higher frequency. For one mechanical revolution, 60 cogging pulses will be observed. The high pole number is desirable as it reduces the size of several components, giving a better torque density with regard to both mass and volume. Without a high pole number, the balance of iron and copper loss will be affected with the majority of the torque produced by applying a large current, resulting in a high copper loss

Table 1. Geometric Parameters of the Proposed Machine Design

Parameter	Value	Unit
Tooth Number	12	ul
Pole Number	10	ul
ID min (with coil)	50.3	mm
OD max (with coil)	109.7	mm
ID Stator Component	60	mm
OD Stator Component	100	mm
Axial Length	66.2	mm
Coil Width	4.5	mm
Turn Number (per coil)	100	ul
Tooth Axial Length	24	mm
Stator Radial Height	20	mm
Stator Coreback Depth	5	mm
Airgap Thickness	1	mm
Magnet Depth	6.2	mm
Magnet Span	110	deg
Insulation Thickness	0.75	mm
Total Coil Distance From Airgap	2	mm
Stator Material	Somaloy_700HR_5P	
Rotor Frame Material	Plastic	
Winding Material	Copper	
Magnet Material	N45SH	

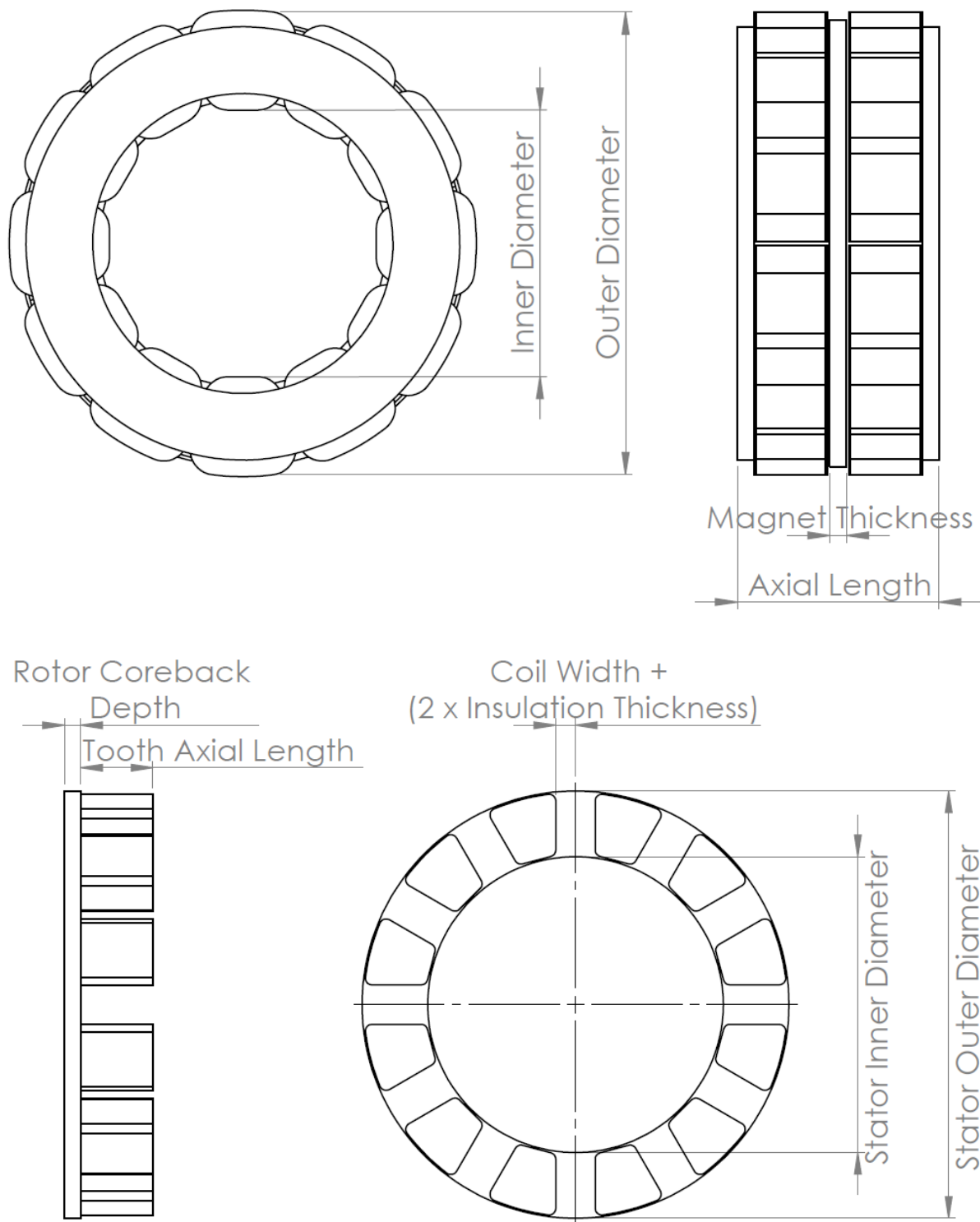


Figure 5. Illustration of the Major Machine Dimensions of a Double-Sided Axial Flux Machine

Model Simulation Setup and Results

JMAG Model Settings

Materials

The soft magnetic composite materials manufactured by Höganäs AB are contained in the JMAG material database. The stator uses advanced material, 700HR 5P, which has a low specific loss, necessary for a component with a varying field throughout. High grade NdFeB magnets are used to provide a large magnet MMF, an important factor with a relatively low permeability material and large effective airgap: no correction is made for any magnet insulation setting applied, and 100% of the volume is assumed to be active material.

Temperatures are set based on steady-state operating criteria: this will weaken the magnet MMF and increase the coil resistance (set manually from a coil path length and temperature dependent resistivity).

Eddy currents are set to be allowed to flow in the stator teeth and coreback, and magnets. The material settings are contained in Table 3.

Table 3: Material Settings

Component	Material	Grade	Temperature (°C)	Eddy Currents
Stator Teeth	SMC	Somaloy® 700HR 5P	-	Yes
Coil Insulation	Plastic	-	-	No
Coil Winding	Copper	103% IACS	120	No
Rotor	Plastic	-	-	No
Magnets	NdFeB	N45SH	100	Yes

Coils

As this is a double-sided AFM configuration there are two stators with mirrored coil configurations, in such a way that when they are opposed the coils are following the same directions.

The phases should be configured as three separate FEM Coil conditions with each condition containing four coils, Group 1 to 4 in Table 4. For a 12 slot motor with 10 poles, the coils are counter-wound in adjacent pairs that are connected in series, each pair can then be connected either in series or parallel. Viewed in the XY plane, the coil directions can be set as clockwise (C) or anticlockwise (AC), see Figure 6 for reference.

Table 4: Coil Arrangement

	Phase A	Phase B	Phase C
Group 1	Coil 1 (AC)	Coil 3 (C)	Coil 5 (AC)
Group 2	Coil 2 (C)	Coil 4 (AC)	Coil 6 (C)
Group 3	Coil 7 (C)	Coil 9 (AC)	Coil 11 (C)
Group 4	Coil 8 (AC)	Coil 10 (C)	Coil 12 (AC)

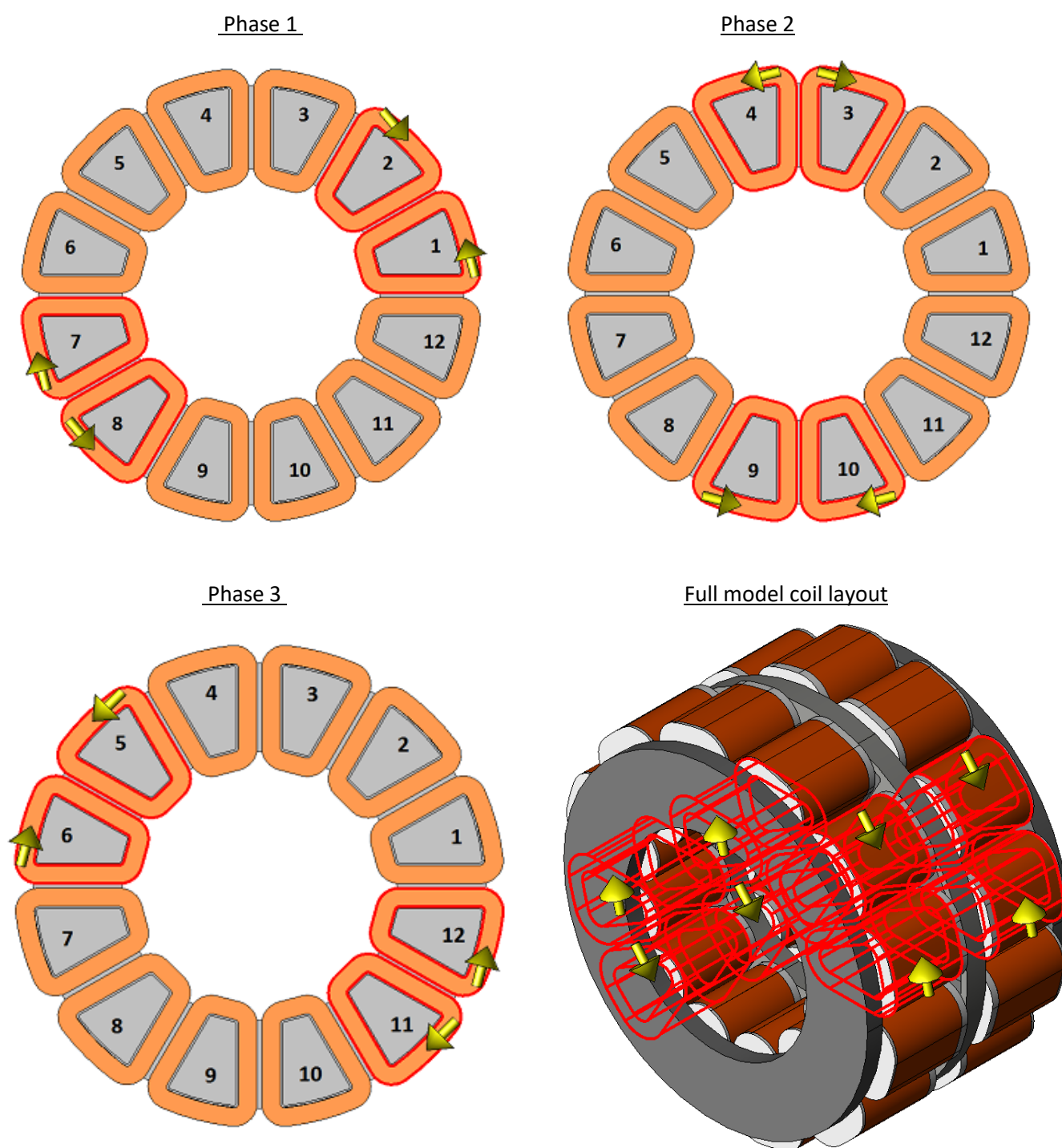


Figure 6. Winding layout for a 12-10 double-sided axial flux machine.

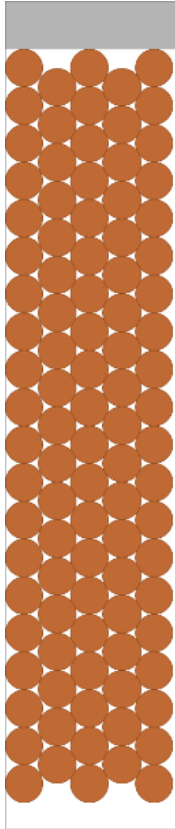


Figure 7:
Coil turn
layout

The coil is made up of 100 turns of 0.9 mm diameter bare copper wire. With grade 2 insulation, the overall diameter is 0.989 mm at maximum tolerances. Each turn is a single strand of wire. A possible coil turn layout for the machine is shown in Figure 7, this should be confirmed with a specialist coil winding company, particularly as turn number increases and the margin for error becomes smaller. Each phase is made up of 2 parallel sets of 4 coils connected in series. The temperature is set to 120 °C and the resistance of each phase can be calculated to 1.076 Ω .

Motion

The motion region is set using the Rotation Motion condition applied to the Rotor Frame and magnet segments. The speed is set as a constant revolution speed (6000 rpm). An initial position is applied with a step-back of 4 degrees mechanical (-4°) to remove the initial transient, this must be reflected in the electrical phase for maximum torque per amp. Nodal Torque and Nodal Force conditions are applied to the Rotor Frame component with the motion region, the latter allowing Z-component forces to be obtained for bearing calculations.

Iron Loss

The Iron Loss condition is set for the Stator Teeth (including the coreback). The calculation method uses Preset 1, which utilises the Apply Loop method and FFT to calculate the hysteresis and in-particle Joule loss, respectively. The bulk eddy loss is the remnant from subtracting the Iron Loss condition values from the total loss density calculated in the field analysis.

The pole number (10) is set and the angular velocity (6000 rpm) is the same as the motion component. No periodicity is included in this example model.

Insulation

The Insulation modelling condition is set due to magnets being split. In the same way laminating a stator core reduces eddy current path lengths, splitting the magnet will help to reduce the Joule loss. The condition applies a perfect insulation surface, which would impact the magnet material content in real terms: this can be adjusted in the material's Magnetic Properties Correction if required.

Circuit

The circuit comprises a three-phase sinusoidal current source with the amplitude set based on the coil current density, frequency defined by the speed and pole number, and phase, dependent on the connection method and mechanical rotor angle. Three FEM coils are set, linked to their conditions in the simulation environment, with turn number and resistance specified: the values are provided in Table 5. It is worth remembering that each phase consists of 2 parallel sets of 4 series connected coils. No leakage inductance is applied. Voltage probes are applied, and terminals added at the nodes to enable the voltage difference to be observed for a delta connection. Figure 8 shows the circuit layout in JMAG.

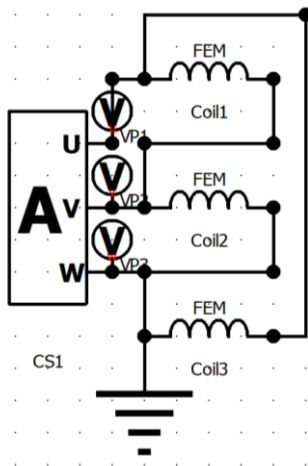


Figure 8: Circuit configuration in JMAG

Table 5: Circuit values

Parameter	Value	Unit
Current Amplitude	15.583	A _{pk}
Frequency	500	Hz
Phase	-110	°
Coil Turns	100	-
Constant Resistance	0.538	Ω

Mesh

Meshing is set relatively coarse on most parts to provide a time efficient solution, solving a full model in a reasonable minutes. Mesh in airgap region is significantly finer. A slide mesh is used with a semi auto mesh generation method and automatic subdivisions applied. For JMAG v18.0 onward, the extended slide plane is set in the properties menu, here with 360 circumferential divisions. This mesh is not suitable for establishing ripple or cogging torque. Mesh parameter values are shown in Table 6, with the resultant model mesh depicted in Figure 9. Alternatively, it is possible to model half or quarter of the machine with natural boundary running through the magnet.

Table 6: Mesh Properties

Properties	Value
Mesh Type	Slide Mesh
Generation method	Semi Auto
Air Region Radial	1.5
Air Region Axial	3
Airgap Faces	1 mm
Element Size of Parts	10
Circumferential Divisions	360

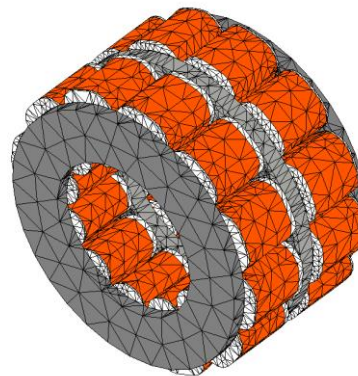


Figure 9: Mesh of DSAFM model

Simulation Results

Continuous Operating Conditions

Rated conditions of 5.1 Nm of torque at 6000 rpm, shown in Figure 10, is reached with a $5 \text{ A}_{\text{RMS}}/\text{mm}^2$ current density, which is a comfortable thermal load for a motor with this type of cooling. Peak line-line voltage is 263.09 V, depicted in Figure 11, which is lower than the specified 350 V, however, there must be some headroom in order to achieve the overload point.

The electromagnetic efficiency at rated conditions is 93.92% (AC skin & proximity losses are not included in the analysis which may reduce the efficiency slightly). Given the small conductor cross section area this is likely to not be a substantial factor.

A short-term overload condition, shown alongside the rated condition in Figure 10, of 12.3 Nm can be met with a $13 \text{ A}_{\text{RMS}}/\text{mm}^2$ current density and the electromagnetic efficiency is 92.4%. The on-load voltage depicted in Figure 12 exhibits some armature reaction as the airgap field becomes less sinusoidal. The simulation results are summarised in Table 7.

Table 7. Simulation Results for the Machine for Continuous Operating Condition

Parameter	Rated	Overload	Unit
Speed	6000	6000	rpm
Frequency	500	500	Hz
Line current	15.58	40.52	A_{pk}
Current density	5	13	$\text{A}_{\text{RMS}}/\text{mm}^2$
Average torque	5.11	12.35	Nm
Average torque (compensated)	5.07	12.29	Nm
Torque ripple at rated current	11.34	5.73	%
On-Load Voltage	263.09	327.91	$\text{V}_{\text{LL-pk}}$
Magnet losses	50.61	60.70	W
Total iron losses	90.12	125.91	W
Three-phase coil losses at 120 °C	65.56	448.36	W
Motor losses	206.29	634.97	W
Mechanical shaft power	3183.99	7720.66	W
Motor efficiency	93.92	92.40	%

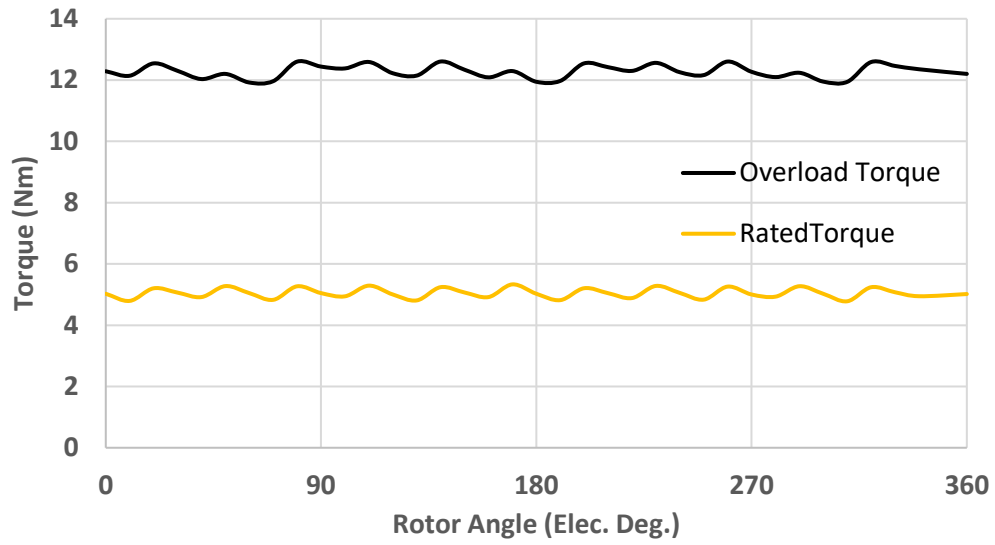


Figure 10. Torque Waveform at 11.02 ARMS and 6000 rpm

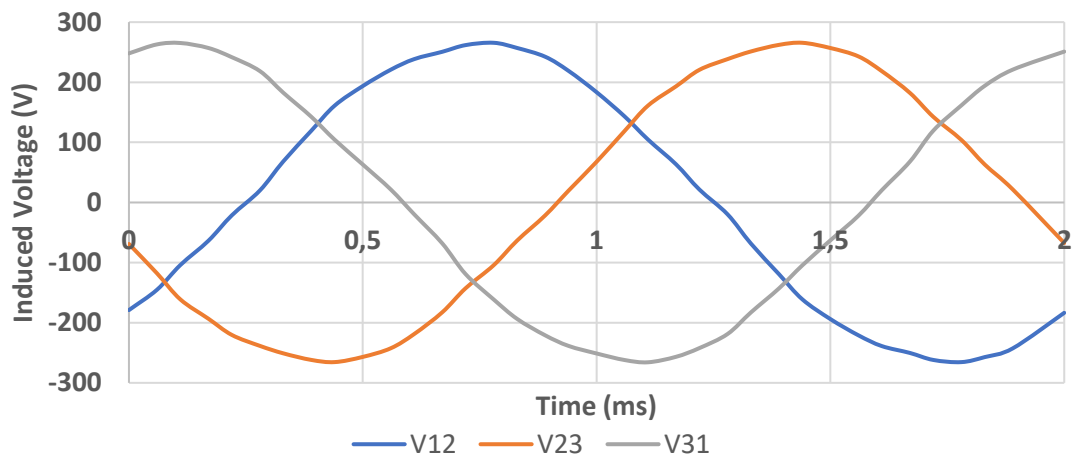


Figure 11. Line to Line On-Load Voltage Waveform at 11.02 ARMS and 6000 rpm.

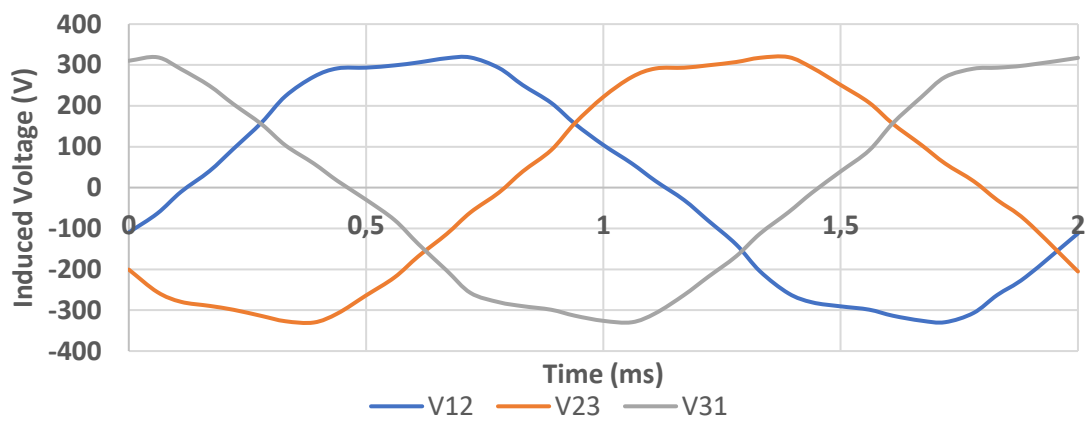


Figure 12. Line to Line On-Load Voltage Waveform at 28.65 ARMS and 6000 rpm.

Demagnetisation

In DSAFM configuration magnets are under higher stress than in SSAFM, therefore it is important to check for demagnetisation. The method for investigating demagnetisation is to observe the permeance coefficient by probing the locations close to the extremities of the magnet segments (where the effect is most noticeable Figure 13): magnets are segmented to reduce eddy current loss, similar to laminating sheet steel.

From Figure 14 it can be seen that lowest permeance coefficient is 0.56, which should allow for a safe operation at 120°C (Figure 15).

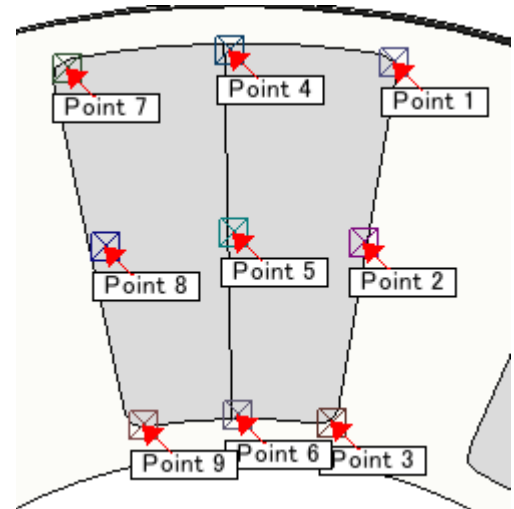


Figure 13: Permeance probes in magnet.

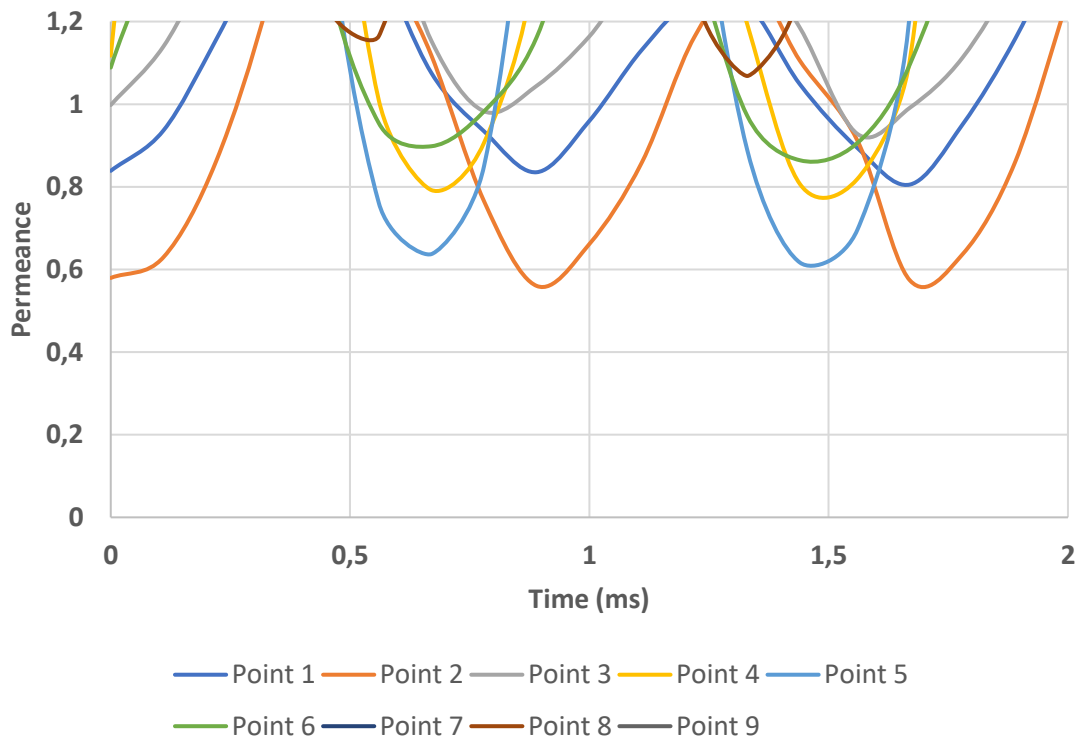


Figure 14. Permeance of probed locations over one electrical cycle for overload condition.

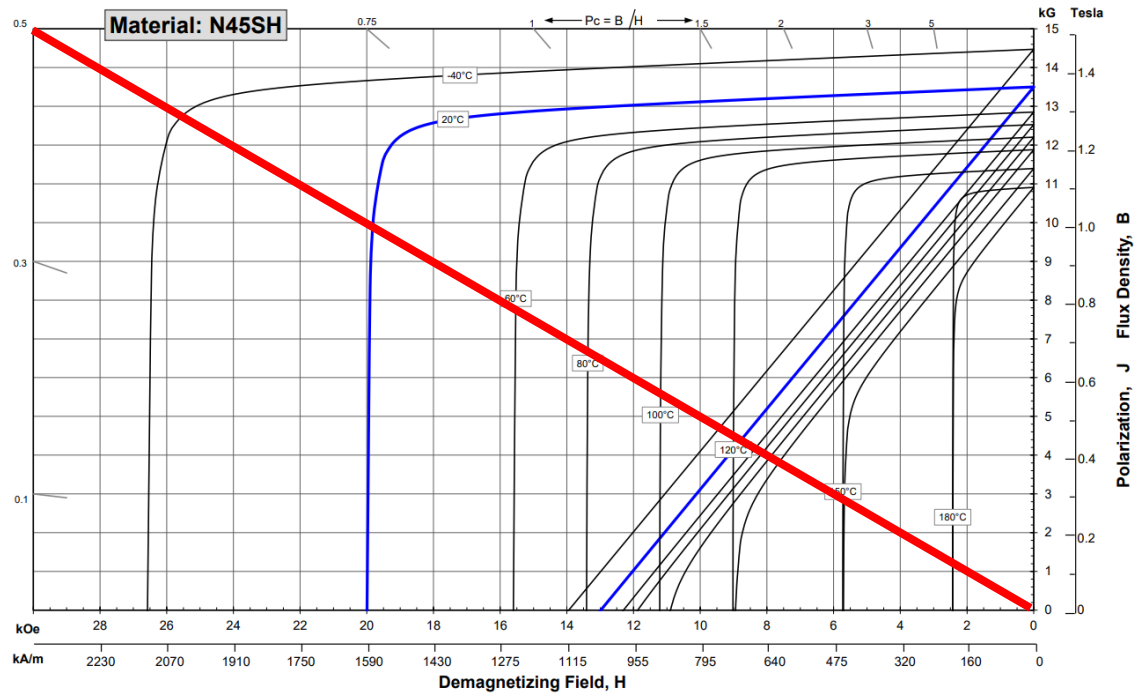


Figure 15. BH characteristics for NdFeB N45SH magnet material (courtesy of Arnold Magnetic Technologies)

Conclusion

A double-sided axial flux machine design has been shown as an example of the potential benefits for utilising SMC in electric motors. The SMC materials produced by Höganäs AB are market leading and provide excellent performance characteristics with an inherent flexibility in the design process. The isotropic nature allows for three-dimensional magnetic flux distribution within the component. For axial flux motors, this is advantageous, where axial and circumferential flux paths exist. Additionally, the ability to control the size and insulation of the iron particles make SMC advantageous, opening the possibilities for applications that have high operating frequencies through an increase in pole number, speed or both. The use of the powder metallurgy process allows for minimal waste during production. Moreover, a variety of geometrical features can be integrated into the SMC die tool, serving functionalities like enhanced mounting features and rounded surfaces for minimising end-winding regions.

Basic design considerations for a DSAFM were presented in the report. The designed machine utilises high strength NdFeB magnets to achieve an overload power of 7.7 kW. The outer diameter is 109.7 mm and the axial length is 66.2 mm, making for a compact design. All operating points are achieved within the specification and efficiencies of over 92% are achieved. Further aspects to consider in the design of a DSAFM with open slots are the AC loss - skin and proximity effects - magnet Joule loss mitigation with active material reduction through insulation, and demagnetisation. These will help to inform any thermal characterisation and provide a more in-depth picture of the motor performance achievable in its operational environment.