Axial Flux Motor Technology – Ideal Topology for hybrid powertrain integration

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Abstract
Axial Flux (AF) motors and generators have been used in niche automotive applications for many years. Given their disk like shape they offer distinct advantages for integration into hybrid powertrains where available length is limited. An overview of axial machine topologies is given and the design and performance laws that govern the sizing of axial flux permanent magnet machines are presented. AP2 hybrid module case study is used to show the benefits and challenges of the axial topology when compared to the radial one. Based on the analytical laws described it is shown that an axial machine can achieve significantly more torque than a size comparable radial machine. 3D finite element analysis is used to fine-tune designs and to investigate loss mechanisms.

The cooling system of the machine is presented in order to show how the integration of coolant passages could be achieved. The possibility of introducing heat barriers into a hybrid powertrain, decoupling the hybrid module from the rest of the powertrain, is also presented. The predicted performance of the machine is presented and compared to the initial test results.

Keywords: Axial Flux, Hybridmodule, P2 Hybrid, Electric Machine, Hybrid Powertrain

1 Introduction
Axial flux electric machines have been known to offer excellent power and torque densities for many years. In fact some of the very first electrical machines were of the axial type [1]. However, despite their apparent performance benefits they have yet to make a significant impact, especially in automotive applications. This lack of impact is most likely due to the difficulty in manufacturing the stators and rotors for these machines. This manifests itself in machines as a reduction in performance when compared with prediction or the cost of manufacturing being prohibitively high. Nevertheless in recent years various axial flux machines have entered the market, especially in applications where high torque and power are required [2,3].

Whilst these machines are starting to gain market acceptance it has to be noted that their use is mainly in niche areas where their shape offers a specific benefit. Most often this benefit is even more pronounced if the machine is fully integrated into the powertrain.

This paper will describe the benefits and challenges of axial flux electric machines. In the first section it is argued that AF technology can
offer great benefits if integrated into hybrid powertrains. The analysis techniques required will be described followed by a specific machine development for a P2 hybrid.

2 Types of Axial Flux Machine

Axial flux machines come in various configurations. In all configurations the magnetic flux passes axially through the air-gap. Within that definition there are variations with respect to the mechanical design as well as different electro-magnetic designs, namely; permanent magnet (PM), interior permanent magnet, induction, brushed DC and switched reluctance machines. For the purpose of this paper only PM machines are considered although similar benefits and challenges are expected if different electromagnetic machine concepts are compared with radial designs.

2.1 Axial flux configurations

AF machines can be designed as single-sided, central rotor or central stator [4, 5], Figure 1. Multiple stages are also used.

![Figure 1: Three basic AFM topologies. Single sided axial flux configuration (a), central stator axial flux configuration (double rotor) (b), and central rotor axial flux configuration (double stator) (c) (Image)](image)

Single sided machines have one rotor and one stator facing each other as shown in Figure 1a [6]. These machines offer the lowest part count but given that they only have one active air-gap they also offer the lowest power. Even if the single air-gap is compensated for with higher copper-content in the winding the impact will be limited as only one stator rear face is available for cooling. A further downside is the attraction force between the rotor and the stator which can be several kN in magnitude.

With regards to cooling, these machines can either be air-cooled or the heat produced in the stator can be removed via indirect cooling over the backside of the stator. This enables conventional cooling using water/glycol and allows the machine to be integrated into a cooling circuit shared with other drivetrain components.

Central stator machine have a single stator sandwiched between two rotors. This machine requires rotors with keeper disks (rotor yokes) acting as return paths for the magnetic flux as shown in Figure 1b [7]. These machines are commonly seen as the most compact designs as no yoke is required in the stator. However in terms of practical implementation there are two major challenges. Firstly, the machine has two rotating disks at its ends with the non-rotating stator in the middle. This makes integration into a vehicle chassis more difficult. In terms of cooling for high performance machines direct liquid cooling in the stator gives the best performance [8]. Alternatively air can be circulated through the machine but this reduces the power output. Indirect cooling as in the other configuration is not possible for this configuration.

Central rotor machines have a single rotor sandwiched between two stators, as shown in Figure 1c [7]. They are effectively two single sided machines fixed together with the rotor yoke removed. The flux passes through the rotor and interacts over two air-gaps with the two stators. This configuration doubles the available cooling area (as there are two stator rear faces available to cool) and thus increases the power output. Another advantage is that conventional coolant can be used to cool the stators indirectly. A further benefit is that the active parts are arranged such that then on-rotating components are ‘on the outside’ of the machine. This eases integration into a vehicle chassis.

These various configurations have been analysed and often the central stator machine is cited as the best solution [8, 9].

Whilst a theoretical analysis might suggest that only one axial flux configuration offers the best solution, it is the experience of the authors that
application-specific integration favours different configurations.

2.2 Simple analysis of AF performance

The performance of an electric machine in terms of its mechanical power and torque can be analysed by looking at the air-gap magnetic field and the shear stress it can create. Assuming that the magnitude of the shear stress is independent of geometry (radial/axial) then in a first approximation the integral over the air-gap multiplied by its radius will give the machine torque.

Figure depicts the dimension of an axial and radial machine. Assuming that the radial machine stator and the axial flux end-windings use up the same space then the active diameter $D_a$ defining the diameter of the air-gap is similar to the largest magnetic diameter of the axial machine.

If the electromagnetic torque is a function of the magnetic shear stress $G$ then the torque for a radial and an axial flux machine is expressed as (1) and (2), respectively. This is achieved by integrating $G$ over the air-gap area and the respective radius.

$$ T_{rad} = \frac{D_a^2}{2} L G $$

$$ T_{ax} = \frac{4}{3} \frac{G D_a^3}{8} D_i^3 $$

For a given machine length it can be seen that the axial machine increases its torque to the power of three of the diameter and the radial one to the power of two.

Whilst equation 2 shows the drastic increase in torque with diameter the effect of the stresses in the rotor needs to be considered when choosing the diameter of machine. As the diameter increases the allowable operating speed needs to be reduced leading to a lower than to the power of 3 increase in output power.

In order to retain the magnets at high rotational speeds a retention feature e.g. banding is needed. It is worth noting that in a radial machine this intrudes into the air-gap forcing the gap to increase whilst in the axial machine it does not impact on air-gap length.

Figure shows how torque and power vary when a radial and an axial machine of originally 300 mm diameter with the same performance have their diameters varied. The power output takes into account rotor stresses and as a result the power output increases only in relation to the power of 2 to the diameter.

For any given space envelope into which a machine needs to be integrated the ratio of $L$ to $D$ will dictate which machine type will produce more torque.

It should not be forgotten that in hybrid applications there is often a need to package a clutch within the inner diameter of the machine. In a radial machine this space is not used, whereas in an axial machine it will result in a output torque reduction as can be seen in Eq. 2. More in-depth analysis by Lipo et all [10] shows that the max. specific torque is achieved when

$$ \frac{D_o}{D_i} = \sqrt{3} $$

(3)
and therefore, depending on the torque and $D_o$ required clutch integration may be possible.

In the experience of the authors an axial machine will give a higher power output than a radial machine when Eq. 4 holds. However it is difficult to generalise as the ratio of internal to external diameter also impacts on the best solution.

\[ L \leq 0.7D_o \]  \hspace{1cm} (4)

3 Machine Positions in Hybrid Applications

Depending on the position of the electric machine in a hybrid powertrain the space envelope available is more beneficial for the application of an axial flux machine. Figure 4 depicts the commonly considered machine positions. The position P0, P1 and P2 commonly require a machine that is short and hence are candidates for axial flux technology integration.

An additional benefit of the central rotor machine in the P2 position is that cold plates at each stator rear face act as thermal barriers and can isolate the electric machine from the heat produced by the engine.

The benefits of axial flux in P3 are less clear and depend on how the specifics of the integration. If the integration is within the gearbox an AF machine can offer a benefit. The same applies to P4 electric axles where the type of integration most often requires long thin and hence radial type machines. However, high power density applications may favour AF technology.

For integration of a machine near or in the wheel AF technology is very attractive [11]

![Figure 4: Possible motor (P) and coupling (C) positions in a hybrid system](image)

4 Manufacturing Options and Design Aspects

The main reason for the slow uptake of the axial flux technology is the lack of suitable materials and manufacturing processes. The disk like shape of the stator posing the major challenge for production. With the advances in soft magnetic composites (SMC) it has become possible to design stators built from sintered SMC segments [8], alternatively a coil of electric steel with stamped slots can be used [13]. Both options offer different benefits and challenges. The relatively high permeability of electric steel offers superior flux carrying capacity over SMC stators. However the forming of the stator core requires complex machinery and can be slow. SMC cores have the potential for high volume automated manufacturing. In terms of performance the benefit of SMC is that it incurs lower losses at high frequencies and carries flux equally well in all three dimensions.

5 Design Methodology

GKN EVO use a range of design tools during the development of bespoke machines. These include both proprietary analytical models and commercially available FEA codes.

5.1 Analytical modelling

Whilst the analysis described in 2.2 was based on a fixed magnetic shear stress, in order to predict actual machine performance, the analytical model presented by [12] is used in this work to perform machine design studies. It is quick to solve, allowing many machine variants to be compared in a short amount of time. The model uses a multi-physics lumped parameter circuitical approach, producing predictions of machine performance by solving coupled electromagnetic, electrical, and thermal circuits. The model takes into account inverter switching strategy, DC voltage levels and environmental conditions. It also allows different winding arrangements, pole numbers, active diameters, lengths, slot geometry, fill factors etc., to be investigated.

The tool is very effective for calculating machines within the calibrated technology range. In order to investigate new machine concepts 3D finite elements analysis is required. This is especially useful for the calculation of losses in the rotor and the stator.

5.2 3D FE modelling

While initial sizing can be done analytically, detailed design requires 3D FEA. This is necessary to quantify important phenomena such as saturation, PM losses, proximity and skin effects etc.
6 Case Study: E Segment Car P2 Machine

To demonstrate the potential of AF machines a case study will be presented for an E segment P2 hybrid. As this machine will have to operate in line with the engine its speed range is governed by it along with the peak cranking torque requirement for a cold engine start.

6.1 Prototype motor construction

A machine required to be placed in between the clutch and engine was designed with the additional requirement of placing the clutch actuator in the middle of the machine. The main performance and size parameters are shown in Table 1.

Table 1: P2 machine parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC Voltage</td>
<td>280-380 V</td>
</tr>
<tr>
<td>I_max</td>
<td>500 A</td>
</tr>
<tr>
<td>n_max</td>
<td>7000 rpm</td>
</tr>
<tr>
<td>n_nom</td>
<td>2800 rpm</td>
</tr>
<tr>
<td>T_nom</td>
<td>90 Nm</td>
</tr>
<tr>
<td>T_max (20s)</td>
<td>240 Nm</td>
</tr>
<tr>
<td>T_max (5s)</td>
<td>350 Nm</td>
</tr>
<tr>
<td>Casing Dia.</td>
<td>290 mm</td>
</tr>
<tr>
<td>Active Dia.</td>
<td>235 mm</td>
</tr>
<tr>
<td>Length inc. Casing</td>
<td>80 mm</td>
</tr>
<tr>
<td>Active Length</td>
<td>58 mm</td>
</tr>
<tr>
<td>Water cooled (55 C)</td>
<td>8 l/min</td>
</tr>
</tbody>
</table>

The machine chassis needs to be designed such that it facilitates the cooling of the motor and allows integration of the machine into the powertrain as shown in Fig 5.

6.2 Performance prediction

The analytical analysis tool [12] was used to investigate the application defined in Table 1. A parametric study was performed and based on its outcome a 3D FEA optimisation was run to ensure losses were modelled correctly. FEA analysis was used to verify the predicted performance from the analytic model and to optimise the machine design, see Figure 7 for a description of the model set up.
Since the prototype motor considered is of the axial-flux topology 3D FEA has been used for accurate electromagnetic analysis. At this stage of the performance investigation a four-segmented PM array is considered. Figure 5 shows the mathematical model of the axial-flux PM motor with a winding sequence U+/V+/W+. Due to rotational symmetry and XY-plane symmetry only the $1/12$ section of the complete motor cross-section needs to be modelled Figure 7b.

Table 2: Comparison of Measured / FEA / Analytical machine parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Measured</th>
<th>Predicted</th>
<th>Analytical</th>
<th>FEA</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{\text{wind}}$ [Ω]</td>
<td>0.055</td>
<td>0.054</td>
<td>n/a</td>
<td></td>
</tr>
<tr>
<td>$T_{\text{nom}}$ [Nm]</td>
<td>103</td>
<td>98</td>
<td>107</td>
<td></td>
</tr>
<tr>
<td>$I_{\text{short}}$ [A_rms]</td>
<td>302</td>
<td>304</td>
<td>306</td>
<td></td>
</tr>
<tr>
<td>$K_t$ [Nm/Arms]</td>
<td>0.92</td>
<td>0.95</td>
<td>0.95</td>
<td></td>
</tr>
<tr>
<td>$K_e$ [V·s/rad]</td>
<td>0.53</td>
<td>0.58</td>
<td>0.54</td>
<td></td>
</tr>
<tr>
<td>$T_{\text{cog}}$ [Nm]</td>
<td>8</td>
<td>n/a</td>
<td>7.5</td>
<td></td>
</tr>
</tbody>
</table>

Short-circuit incidents on traction motors may have serious impact on traction motors and/or vehicle stability. The most common electric drive faults can be categorized as: mechanical failures, control failures, and electrical failures. The last one mostly depends on inverter failure and winding short circuit. Figure 8 shows the simulation results of winding short-circuit with the motor operating at different speeds with 0 Nm constant loads. The figure shows that the machine operates at higher speed than 1000rpm the torque is rapidly decreases and is more stabilized. The significant increases of torque at short-circuit operation can be seen in range of speed 125rpm-500rpm, the peak torque at 250rpm is 160Nm (FEA prediction).

Figure 9: Prototype machine on test
The test arrangement is shown in Fig.9. The shaft of the prototype motor is directly coupled to a dynamometer load machine. The test motor is supplied with coolant from a temperature controlled source. Temperatures are measured at various positions the stator in order to ensure that hotspots can be captured.
The power loss associated with the PM rotor assembly is important as excessive rotor temperature may result in premature failure. Cooling of a central rotor is challenging and hence the reduction of losses in the magnets is paramount. It is obvious that high rotor temperature leads to a reduction in the torque and can be the cause of irreversible demagnetization of the PM array. The temperature of the PM array has a significant influence on the loss predictions. This is because the electrical conductivity of PM material is temperature dependent.

3D FEA has been employed to model the induced eddy-current loss. These losses are induced by the permeance variations caused by stator slotting and from the armature reaction field [14-18]. The armature reaction is caused by the higher order spatial harmonics of the winding distribution. In the present work, the phase current will be assumed to be sinusoidal.

Fig. 10 shows the results of the magnet eddy-current distributions at open-circuit operation when the rotational speed is 1000rpm. In this analysis the PM array was assumed to have a fixed, uniform temperature of 25°C. The magnet loss was computed as:

$$ P_{PM} = \iiint V E \cdot J dV = \rho \iiint V J^2 dV $$  \hspace{1cm} (5)$$

Where $E$ is the electric field strength, $J$ is the current density within the PM and $\rho$ is the resistivity of the PM ($1.6 \times 10^{-8} \Omega \cdot m$).

7 Conclusions

The application of AF technology for integration into hybrid powertrains can offer a significant torque and power increase over conventional technologies. Better understanding of the design and manufacturing process make these machines feasible.

Table 3 below shows examples of machines developed by GKN EVO. The machines with active Ø 305 and 235 mm have been specifically developed for integration into hybrid powertrains in the P2 position.

<table>
<thead>
<tr>
<th>Active Ø [mm]</th>
<th>360</th>
<th>305</th>
<th>280</th>
<th>235</th>
<th>235</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active L [mm]</td>
<td>74</td>
<td>59</td>
<td>72</td>
<td>70</td>
<td>58</td>
</tr>
<tr>
<td>M total [kg]</td>
<td>40</td>
<td>n/a</td>
<td>31</td>
<td>24</td>
<td>n/a</td>
</tr>
<tr>
<td>M active [Kg]</td>
<td>24.2</td>
<td>15.8</td>
<td>16.8</td>
<td>12.4</td>
<td>9.8</td>
</tr>
<tr>
<td>$n_{max}$ [krpm]</td>
<td>5</td>
<td>7.5</td>
<td>8</td>
<td>12</td>
<td>6.5</td>
</tr>
<tr>
<td>T cont. [Nm]</td>
<td>250</td>
<td>155</td>
<td>145</td>
<td>100</td>
<td>97</td>
</tr>
<tr>
<td>T max(20s) [Nm]</td>
<td>660</td>
<td>310</td>
<td>350</td>
<td>250</td>
<td>240</td>
</tr>
</tbody>
</table>

Part of the Powertrain

References


Authors

Michael U. Lampérth graduated from Winterthur Polytechnic, Switzerland, in 1989 and received the PhD from Imperial College in 1999, where he was a lecturer until 2010. He was founder and CTO of Imperial College spin-out company EVO-Electric, which was formed to commercialize innovative axial flux electrical motors and generators. He is currently CTO of GKN EVO and involved in collaborative R&D programs between Industry and Universities in the area of electric motors and hybrid systems.

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