Performance Analysis of Electric Motor Technologies for an Electric Vehicle Powertrain

White Paper

1 Introduction

Due to the increasing concern surrounding climate change and inner city air pollution, and the strong consumer demand for ‘next-generation’ vehicles such as the Tesla Model 3, pure battery electric vehicles are now seen as the future of the automotive industry. The development of a battery electric vehicle powertrain is a complex system problem. Achieving an optimised system design requires evaluation of many different concepts and topologies as well as detailed understanding of the system interactions. These interactions are typically cross specialism or discipline, involve different teams and often require multi-physics analysis. Design and simulation tools are crucial to the evaluation of different design topologies as well as identifying and understanding important system interactions.

In this paper, we focus on the design and development of the electric motor(s) in an EV powertrain and consider how the different design choices—such as motor topology, winding type and cooling system—can be compared and evaluated with consideration to the overall system impact of these design choices. The first section of the paper looks at a comparison between an interior permanent magnet (IPM), induction (IM) and wound field synchronous (WFSM) motor design in an EV application. The second part of the paper takes the PM machine design and considers the trade-off between hairpin and stranded winding technologies. Finally, three different cooling types are compared: water jacket cooling, oil spray cooling, and combined water jacket and air cooling.

The results presented in the paper are based upon analysis from Motor-CAD software.

2 Motor type comparison

The three machine types that are compared have been designed for the same specification shown in Table 1. The IPM, IM and WFSM motor types have been chosen for this comparison as all three can be seen in mass production EVs currently available on the market. The machines have been sized to achieve a given peak performance requirement, while the continuous performance varies between the designs. The motors have been designed within a fixed maximum stator outer diameter and each design shares the same water jacket cooling method.

The motor types will be compared in terms of mass, cost, continuous performance, efficiency and energy usage over typical drive cycles.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Torque</td>
<td>350 Nm</td>
</tr>
<tr>
<td>Peak Power</td>
<td>150 kW</td>
</tr>
<tr>
<td>Maximum Speed</td>
<td>12000 rpm</td>
</tr>
<tr>
<td>DC Link Voltage</td>
<td>400Vdc</td>
</tr>
<tr>
<td>Maximum current</td>
<td>500Amps</td>
</tr>
<tr>
<td>Stator Outer Diameter</td>
<td>250 mm</td>
</tr>
<tr>
<td>Cooling type</td>
<td>Water jacket</td>
</tr>
<tr>
<td>Cooling temperature</td>
<td>65°C</td>
</tr>
<tr>
<td>Coolant flow rate</td>
<td>6.5 l/min</td>
</tr>
</tbody>
</table>

Table 1 – Specification

2.1 PM design

The cross section for the PM machine design is shown in Figure 1. It is a 48 slot 8 pole (48s8p) interior PM machine and the rotor is a double layer configuration. This configuration is used to minimise the permeability of the d-axis. This results in a difference in inductance between the magnet axis (d-axis) and the interpolar axis (q-axis), maximising the potential to utilise reluctance torque.
There are a number of flux guides in the rotor. The function of these are to create local saturation in areas of the rotor, which guides the flux from the magnet into the airgap and maximises the utilisation of the magnet torque component. The magnets are made from sintered rare-earth magnets, neodymium iron boron (NeFeB) type of grade N42UH. The laminations are made from non-oriented semi-processed silicon iron, 0.35mm thick, electric steel of grade M250-35A.

To minimise torque ripple and voltage harmonics a number of techniques are used. The rotor utilises step skewing, which segments the rotor into three sections axially and displaces each slice by an offset angle, this can be seen in Figure 2. The effect of this step skewing is to cancel certain harmonics in the torque ripple and cogging torque waveform which may be caused by the interaction between the number of poles and slots in the machine.

Another technique employed to minimise harmonics is to profile the shape of the rotor surface through the use of notches, which can be seen in Figure 3. The rotor surface profiling can be used to control the harmonics in the airgap flux density waveform. This approach can minimise torque ripple and voltage harmonics as well as radial force harmonics, which can give rise to unwanted NVH behaviour.

The winding uses a distributed winding where each turn is made up of multiple strands of small round wires. A single layer winding is adopted, which means that each slot is occupied by a single coil and phase. The coil pitch is 5 slots, which is shown in Figure 4, and there are 6 turns per coil each with 15 strands per turn. The slot fill factor, which is the ratio of copper to slot area, is 40%. The slot cross section is shown in Figure 5. The winding uses two parallel paths per phase and this can be seen in the linear winding pattern in Figure 4.

In Figure 7, the open circuit flux density in the rotor and stator lamination is shown. It can be seen from this flux density plot that there are small areas of high saturation in the rotor bridges that help to guide the magnet flux into the airgap. The flux density distribution during on load conditions (torque = 350Nm) is shown in Figure 8. The peak flux density in the stator tooth and back iron is around 1.8T, which is typical for machines that have a good utilisation of the magnetic material while maximising available slot area.

The open circuit, line-line back-EMF waveform at 500rpm (shown in Figure 6) has a minimal harmonics content, being quasi-sinusoidal due to the impact of rotor skewing.
The torque waveform as a function of rotor position is show in Figure 9. As with the back-EMF waveform, the multi-slice rotor is helping to minimise harmonics. The overall torque ripple is low at 4.4%.

The flux density distribution in the stator and rotor lamination for peak torque operation is shown in Figure 13. The peak flux density in the rotor teeth, stator teeth and stator back iron is in the range of 1.8-2T.

2.2 IM design

The cross section for the induction machine design is shown in Figure 10. The design has 72 stator slots and 84 rotor bars. It is a 6-pole rotor with a die-cast copper cage. The laminations use M250-35A grade electrical steel. The rotor bars have a 5° mechanical skew applied to minimise torque ripple.

The IM design uses a single layer winding with a 40% slot fill factor and the slot cross section is shown in Figure 11. The winding has 3 turns per coil with 15 strands in hand per turn and 2 parallel paths are used per phase. The linear winding pattern for a single phase is shown in Figure 12.

The torque is calculated using a 2D FEA transient solution, including rotor rotation, and hence takes into account the influence of space harmonics on the rotor bar currents and torque ripple. The time-averaged loss density in the rotor bars over one electrical cycle are shown in Figure 14. An equivalent conductivity correction is applied to rotor bars in the 2D FEA solution to account for the influence of the end rings. The torque waveform calculated using the 2D FEA solution is shown in Figure 15. The torque ripple is shown as 17%, however we are not accounting for the 5° mechanical skew in this calculation which, if accounted for, would reduce the torque ripple to acceptable levels.
2.3 WFSM design

The wound field synchronous machine design uses a 48-slot stator and an 8-pole salient rotor. The radial cross section is shown in Figure 16. The laminations use the same grade of electrical steel (M250–35A) as the PM and IM machine designs.

![Figure 16 - Radial cross section for the WFSM design](image1)

The salient pole rotor is shown in Figure 17. The field from the rotor is created by the concentrated windings around each tooth. DC current is applied to the windings through slip rings, which allows the excitation in the rotor to be controlled. The rotor winding has 132 turns and up to 16A of DC current is applied to the windings. The rotor slot cross section is shown in Figure 18.

![Figure 17 - 8-pole salient rotor](image2)
![Figure 18 - Rotor slot cross section](image3)

The WFSM can utilise a combination of alignment and reluctance torque, as with the PM machine. However, in a WFSM the q-axis inductance is lower than the d-axis and hence reluctance torque is produced only with positive d-axis current. As such, the maximum torque/amp angle will occur when the phase advance angle, \( \gamma \), is less than zero (\( \gamma < 0 \)). Here the current waveform is retarded with reference to the voltage induced by the rotor field. This is unlike the PM machine case, in which the MTPA angle occurs when \( \gamma \) is greater than zero (\( \gamma > 0 \)) or the current waveform is advanced with reference to the voltage induced by the rotor field. However, once into the field weakening region the control strategy for the WFSM uses a combination of reduced DC rotor excitation and negative \( I_d \) current (\( \gamma > 0 \)) to extend the speed range of the machine.

![Figure 19 - Radial winding layout for a single phase](image4)

The winding uses the same pattern as the PM machine detailed above—6 turns per coil are utilised with 15 strands per turn. Again, a 40% copper slot fill factor is used. The coil spans for a single phase are shown on the radial section in Figure 19.

![Figure 20 - Flux density at 350Nm](image5)

The flux density distribution of the WFSM on load conditions, at 350Nm, is shown in Figure 20. Due to the highly salient rotor there is a significant level of space harmonics generated. This leads to a torque ripple of 17% and high levels of total harmonic distortion (THD) in the on-load voltage waveform, as shown in Figure 21.

![Figure 21 - On-load line-line voltage waveform](image6)
2.4 Cooling system

The same cooling system—a spiral water jacket—is used for all the machine designs compared in this section of the study. The geometry of the housing with the cooling channels is shown in Figure 22 and the channels run over the active section of the stator only. The water jacket has a 65°C inlet temperature and an ethylene glycol water (EGW) coolant. A 6.5 l/min coolant flow rate is used.

Although traction machines in EV applications do not operate continuously, it is typical to use continuous performance curves to understand the thermally limited characteristics of the machine and to compare between different design choices. The continuous performance characteristics are calculated by setting maximum temperature limits for different components of the machine and calculating the maximum torque that can be achieved continuously within those limits across the full speed range. This requires coupled solving of electromagnetic, loss and thermal models, with a maximum torque/amp control strategy that includes field weakening behaviour. The thermal behaviour is calculated using a sophisticated lumped-parameter model of the machine, which considers conduction, convection and radiation heat transfer in radial and axial directions. The lumped-parameter thermal model is based upon proven modelling techniques and correlations which have been built into Motor-CAD software.

To compute the continuous performance curve, the stator winding for each machine is set to a maximum winding hotspot of 180°C, while the magnet in the PM machine is limited to 160 °C, the IM rotor bar to 220 °C and the WFSM rotor winding to 180 °C. The continuous torque/speed and power/speed curves for all three machines can be seen in Figure 25 and Figure 26 respectively. The PM machine has the best continuous torque at lower speed, however as the frequency increases the IM machine shows improved continuous torque above 9000rpm. The WFSM has the lowest continuous capability, mainly due to excessive rotor temperature, and ideally the WFSM requires a rotor cooling mechanism.
2.6 Axial dimension and mass

PM machines typically have higher improved torque density in comparison to other machine types, due to the high value of magnetic loading that can be achieved using rare earth permanent magnets. In this example, the stator outer diameter of all three machine types is consistent and the axial length is varied to achieve the peak performance requirements.

A comparison of the axial dimensions and mass of the machine designs is shown in Table 2. The PM machine has an active length of 100mm compared to 120mm for the IM and WFSM machines. The total length of the IM machine is the largest as it has the longest end windings (due to the coil pitch from the winding pattern). The IM also has the highest mass of the machines.

The magnets will be the most expensive component in the PM machine. As such, the PM machine will have the highest cost if the machine is considered in isolation.

<table>
<thead>
<tr>
<th></th>
<th>PM</th>
<th>IM</th>
<th>WFSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active length (mm)</td>
<td>100</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>End winding overhang (mm)</td>
<td>30</td>
<td>40</td>
<td>30</td>
</tr>
<tr>
<td>Total length (mm)</td>
<td>160</td>
<td>200</td>
<td>180</td>
</tr>
<tr>
<td>Steel (kg)</td>
<td>26.1</td>
<td>33.4</td>
<td>28.17</td>
</tr>
<tr>
<td>Copper (kg)</td>
<td>5.05</td>
<td>13.7</td>
<td>8.5</td>
</tr>
<tr>
<td>Magnet (kg)</td>
<td>2.05</td>
<td>0</td>
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<tr>
<td>Total (kg)</td>
<td>33.2</td>
<td>47</td>
<td>36.7</td>
</tr>
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</table>

2.7 Efficiency

Optimisation of the efficiency of an electric machine is crucial in a battery electric vehicle traction application. The battery is the most expensive component in the vehicle. Using the energy from the battery in the most efficient way possible maximises the range of the vehicle and/or enables a smaller and less expensive battery to be used to achieve a given target range. The efficiency of the motor has an impact on the mile/kWh rating of the vehicle through energy supplied during motoring operation and energy recovered during regenerative braking.

2.7.1 Efficiency maps

The efficiency maps for the PM, IM and WFSM are shown in Figures 27, 28 and 29. The PM machine has the highest efficiency as a result of the low loss from the permanent magnet rotor excitation. The peak efficiency for the PM machine is 96.8%, with a large 96% efficiency contour from 2-9krpm. The high efficiency region is well placed at low-medium torque levels and corresponds well to the typical drive cycle residency plot.

The induction machine has a slightly lower peak efficiency of 95.5%. The peak efficiency region occurs at higher speeds from 7-12krpm. At lower speeds, for example at 50Nm and 2krpm, the PM machine has 4% higher efficiency than the IM machine design. However, at higher speed and lower torques the opposite is true and the IM has higher efficiency than the PM machine. This is due to the iron losses that are generated in the PM machine, even at no-load, as well as the field weakening ($I_d$) current that is required in the PM machine at higher speeds to suppress induced EMF from the rotor excitation to stay within the maximum DC link voltage.

The WFSM has a similar peak efficiency to the IM machine, the maximum efficiency region occurs from 5-10krpm and at higher torque levels than the PM or IM machine.
2.7.2 Loss calculation

The main losses components that exist in electrical machines and are calculated in the efficiency maps above are DC winding loss, AC winding loss, Iron loss, Magnet loss (PM machine only), rotor bar loss (IM machine only), bearing loss and windage loss. A detailed explanation of all the computational methods used to generate the results is beyond the scope of this paper, however it is useful to understand how some of the more challenging frequency-related loss components have been calculated which are used in the efficiency results within this section.

Each of the analysed machines has frequency-related proximity losses in the windings. These losses are a result of induced eddy currents in conductors, caused by the alternating currents in adjacent conductors. These eddy currents cause an uneven current density distribution in the conductors that leads to an effective increase in resistance and hence increased losses. The calculation of the proximity losses for each machine has been achieved by computing the leakage flux density in the slots during operation using FEA. The leakage flux density, along the height of the slot and variation over the electrical cycle, is used to calculate the magnitude of the loss and distribution of the losses in the slots.

This computation is performed at a range of operating points to evaluate, for example, how AC losses vary with current magnitude and phase advance. As all three machines have a multi-stranded winding, precise knowledge of the position of each conductor is unavailable due to the random nature of the winding. As such, the height of the turn (bundle) is unknown and an assumption of the aspect ratio of the bundle (ratio of height to width) is used based upon previous experience.

To calculate the losses in the electrical steel, typically known as iron losses, the Steinmetz model is used. This is an empirical technique that post-processes information from the flux densities calculated using FEA to compute the loss. The electrical steel lamination material datasheet provides the values of loss density at a range of flux densities and frequencies. This loss data is used to curve fit to find a set of coefficients for the Steinmetz model. The FEA calculation is then performed over the full electrical cycle and the flux densities for each element of the FEA mesh are used to compute the value of the loss. One of the challenges with the calculation of iron losses is that the material properties are significantly affected by the manufacturing processes, such as stamping and shrink fitting. As such, a build factor has to be applied to the calculation to account for this. This build factor is typically chosen from experience and in this paper we have used a value of 1.6.

Many of the loss components are caused due to induced eddy currents: iron loss, magnet loss, rotor bar loss and AC winding loss. In the calculations in this paper we have assumed that the machines are driven by an ideal sine-wave current provided by the inverter. In reality, there will be some higher harmonic components of the current waveform caused by the switching of the inverter. These can lead to increased losses, particularly in conductive components of the rotor, such as the rotor bars or magnets. These switching related, time harmonic loss components are not included as it requires detailed co-simulation of the inverter with the motor, including switching behaviour of the power electronics devices, modulation strategy and current control loops. This information is generally not known at the design stage and the detailed co-simulation is also computationally intensive due to the small-time base required for the inverter simulation, particularly if coupled to an FEA solution. As such, these effects are typically evaluated at a later stage in the development lifecycle.

However, clearly these system interactions can be important and it is conceivable that they could have an influence on some major decisions, such as choice of electric motor technology for an EV powertrain. The use of Motor-CAD alongside advanced couplings to other dedicated simulation tools enables engineers to accurately and computationally efficiently model these detailed system interactions at an early stage in the development process, when design choices are still open and the cost of change is low.

2.7.3 Drive cycle modelling

To understand the impact of different motor types on the energy use we need to model the performance for each design across a drive cycle. A simple kinematic vehicle model is used to convert the standard WLTP and US06 time/speed vehicle profiles into a time/torque/speed profiles for the motor. The vehicle model parameters are shown in Table 3. The model assumes that the vehicle is driven by a single electric motor and 100% of the braking is regenerative. In addition, no gradients are assumed for the cycle.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Vehicle mass</td>
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<tr>
<td>Rolling resistance coefficient</td>
<td>0.0054</td>
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<tr>
<td>Air density</td>
<td>1.225 kg/m³</td>
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<tr>
<td>Frontal area</td>
<td>2.81 m²</td>
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<tr>
<td>Drag coefficient</td>
<td>0.24</td>
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<tr>
<td>Wheel radius</td>
<td>0.35 m</td>
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<tr>
<td>Mass correction factor</td>
<td>1.04</td>
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<tr>
<td>Gear ratio</td>
<td>10:1</td>
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</table>

The WLTP drive cycle points that are calculated from the vehicle model are plotted onto the PM machine efficiency map in Figure 30 and each point represents 1s on the cycle. It can be seen that both the motoring and generating operating points are well within the capabilities of the machine and that the majority of operation is at low torque in the mid speed range.

The calculated energy usage is shown in Table 4. The PM machine has lower losses and improved efficiency over both the WLTP and US06 drive cycles, while the IM and WFSM show similar energy use over both cycles. Therefore, the PM machine would either extend the range of the vehicle or enable a reduced battery capacity/mass for a given fixed range.
Performance Analysis of Electric Motor Technologies for an Electric Vehicle Powertrain

2.7.4 Dual motor configuration

A recent trend in premium EVs is the use of a dual motor configuration, with an electric machine on each axle. This enables all wheel drive and fast acceleration capabilities. This configuration can be seen in the Jaguar I-PACE, Audi e-tron, Mercedes EQ, Tesla Model 3 performance, Tesla Model S and Tesla Model X.

While dual motors would be used for more aggressive drive cycles, a large percentage of the vehicle operation will require significantly lower torque than the peak capability of the motors, such as the WLTP cycle shown in Figure 30. These low torque operating points could feasibly be provided by a single motor.

In this case the optimal energy usage would likely be achieved by using the combination of a PM machine and an induction machine by exploiting the different efficiency characteristics. As the induction machine has practically zero magnetic loss when not energised, i.e. open-circuit conditions, it could be used exclusively for when the peak torque from a single motor was insufficient or if all wheel drive capability was required. The Tesla Model 3 Performance is an example of this configuration with an IPM machine on the rear axle and an induction machine on the front axle.

2.8 Summary of motor type comparison

We have looked at a comparison between an interior permanent magnet, induction and wound field synchronous machine in a battery electric vehicle application. Each of these machine types can be seen in mass production electric vehicles, with the interior PM machine the most common configuration. The three motor types have been compared in terms of mass, cost, continuous performance, efficiency and energy usage over typical drive cycles.

It has been found that the PM machine offers improved efficiency and reduced mass/volume at higher cost. Due to higher efficiency the PM machine would either extend the range of the vehicle or enable a reduced battery capacity and mass for a given fixed range. This may result in a lower overall system cost for the PM. However, the PM and IM machines show improved efficiencies at different areas of the map and if a dual motor configuration is used this could be advantageous. The WFSM has similar performance to the IM however the thermal performance is very constrained on rotor temperature and ideally some rotor cooling system is required in this example.

3 Winding technology comparison

In the previous section each motor design used the same winding technology: a multi-stranded distributed winding. However, a growing trend in electric machines is the use of hairpin windings, these are pre-formed rectangular bars which are inserted into the slots and joined at one end.

Hairpin windings have distinctly different manufacturing and assembly processes in comparison to traditional stranded windings. This may have manufacturing cost benefits and the repeatability is much better because the position and placement of each conductor is well known and controlled. In addition, the end windings are typically more compact in hairpin wound machines and an example can be seen in Figure 31. However the rectangular conductors also have some drawbacks, such as significant AC winding losses. In this section we consider the performance of the two winding technologies and to do this we will compare the interior PM machine design from the previous section with both a stranded winding and a hairpin winding.

3.1 Design comparison

The PM machine design is carried over from the previous section: a 48 slot 8 pole IPM machine with 6 turns per coil. The hairpin winding variant utilises a parallel slot geometry. A comparison of two slot cross-sections are shown in Figure 32.

<table>
<thead>
<tr>
<th></th>
<th>PM</th>
<th>IM</th>
<th>WFSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Loss – WLTP (Wh)</td>
<td>255.53</td>
<td>310.25</td>
<td>312.62</td>
</tr>
<tr>
<td>Av. Efficiency (%) – WLTP</td>
<td>94.32</td>
<td>93.17</td>
<td>92.79</td>
</tr>
<tr>
<td>Total Loss – US06 (Wh)</td>
<td>176.09</td>
<td>223.57</td>
<td>214.9</td>
</tr>
<tr>
<td>Av. Efficiency (%) – US06</td>
<td>94.72</td>
<td>93.39</td>
<td>93.44</td>
</tr>
</tbody>
</table>

Table 4 – Energy usage and average efficiency over the cycle

Figure 30 – WLTP drive cycle points on PM machine efficiency map

Figure 31 – Hairpin end windings in a PHEV traction motor

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The losses for single arbitrary operating point at 100Nm and 8000rpm are shown in Table 5. The effect of transposition and of circulating currents between parallel paths is neglected. It can be seen that while the DC losses are lower in the hairpin winding, the AC winding losses are much higher and that the total overall winding losses are actually higher in the hairpin winding. The AC losses are strongly related to the height of the turn in the radial direction and as such it is desirable to reduce the conductor height as much as possible to minimise AC loss. This is typically restricted by a conductor aspect ratio manufacturing limitation. The loss distribution per conductor over a single electrical cycle is shown in Figure 33. It can be seen that the loss is unevenly distributed throughout the slot and is concentrated at the slot opening. This characteristic is important to consider particularly when performing thermal analysis as it can significantly impact winding hotspot temperature.

### 3.2 Performance curves

The peak performance of the two design variants is very similar as the active length and number of turns is unchanged, and the characteristics can be seen in Figure 34. The small differences arise from the change in the tooth shape in the hairpin winding and the increased winding resistance at higher frequencies.

The continuous torque and power characteristics are shown in Figure 35 and Figure 36. It can be seen that at lower speed the hairpin winding offers improved continuous torque due to reduced DC winding losses and improved thermal conductivity across the slot in the tangential direction. However, at higher speeds these advantages are counteracted by the higher levels of AC winding loss in the hairpin winding and the stranded winding shows improved continuous torque and power above 7000rpm.
3.3 Efficiency

The efficiency maps for the stranded and hairpin winding design are shown in Figure 37 and Figure 38. As discussed in the previous section, the peak efficiency for the stranded winding machine is 96.8% with a large 96% efficiency contour from 2-9krpm. The hairpin winding has a slightly higher peak efficiency of 97.10% with a 97% efficiency contour from 3-7krpm. The hairpin winding has improved efficiency at lower frequencies however once above 8000rpm the efficiency of the stranded winding is generally higher than the hairpin.

3.4 Summary of winding technology comparison

In this section we have considered the performance differences between a hairpin and a stranded winding interior PM machine design for an EV traction application. We have discussed how the hairpin winding offers advantages in terms of lower DC winding, reduced axial dimensions and improved manufacturing repeatability. In terms of performance the hairpin winding shows high continuous torque and efficiency when compared to a stranded winding. However, the AC losses in the hairpin winding can be significant and the impact of them on the continuous thermal performance at higher speeds needs to be considered at an early stage in the design process.

4 Cooling system comparison

In this final section of the paper different cooling systems for EV traction motors are considered and compared. For this comparison the interior PM machine with a hairpin winding is carried over from the previous section and three variants are then compared, each with different cooling systems: water jacket cooling, water jacket with internal air circulation, and oil spray cooling. All three of these cooling systems can be seen in mass production motors for EV traction applications.

4.1 Water jacket cooling

The water jacket cooling approach is a typical approach for cooling electric machines in traction applications. This can be seen in vehicles such as the Nissan Leaf and BMW i3. The axial cross section for the IPM machine with a spiral water jacket is shown in Figure 39. The coolant is EGW 50/50 with a 65°C inlet temperature and a 6.5l/min flow rate.

Table 6 – Energy use over WLTP and US06 cycles

<table>
<thead>
<tr>
<th></th>
<th>Stranded IPM</th>
<th>Hairpin IPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Loss - WLTP (Wh)</td>
<td>255.53</td>
<td>241.24</td>
</tr>
<tr>
<td>Av. Efficiency (%) - WLTP</td>
<td>94.32</td>
<td>94.62</td>
</tr>
<tr>
<td>Total Loss - US06 (Wh)</td>
<td>176.09</td>
<td>165.31</td>
</tr>
<tr>
<td>Av. Efficiency (%) - US06</td>
<td>94.72</td>
<td>95.03</td>
</tr>
</tbody>
</table>
4.2 Water jacket and internal circulating air

Here the water jacket cooling is modified to include internally circulating air driven by a shaft-mount fan. As shown in Figure 40, air is circulated between cooling channels in the rotor and in the housing, the air is cooled as it passes through the housing acting as a heat exchanger between the air and the water jacket. The advantage of this system is to reduce the air temperature inside the machine and hence provide air cooling to the rotor and magnets while the motor is still a sealed, closed unit. This potentially enables a cheaper grade magnet to be used with less dysprosium, as the maximum operating temperature of the magnet is lowered. The axial cross section of the design is shown in Figure 40 in which the air-cooling path is shown. This cooling set-up is used in the BMW 225xe.

![Figure 40 – Water jacket + air cooling, axial cross-section](image)

In this example both of these methods are combined, oil is passed through the shaft and thrown off onto the end windings. In addition, a set of axial channels are used to pass oil along the axial direction with nozzles on both ends of the channel to distribute oil over the end windings. This also has the advantage of cooling the active section of the machine in a similar manner to an axial water jacket. This is a similar approach to the cooling method used in the Toyota Prius MY2017. The cooling paths are shown in the cross section below (Figure 41). In the model we have used ATF with an inlet temperature of 80°C, a flow rate of 4 l/min is assumed for the shaft oil and 8 l/min for the stator oil.

![Figure 41 – Oil Spray cooling, axial cross section](image)

4.3 Oil spray cooling

Direct oil spray cooling of conductors is a growing trend in which transmission fluid (ATF) is applied directly to the end windings of the machine to remove heat. The oil is removed from the machine through a sump and re-circulated through the vehicle cooling system. In comparison to water cooling, the use of oil cooling has potential cost benefits as the oil cooling system can be shared with the transmission and the cooling is quite effective due to a high heat transfer rate between the end windings and the coolant oil.

There are generally two ways of applying the oil to the end windings, either by passing oil through a hollow shaft and using the centrifugal forces during rotation to throw oil onto the end windings. Alternatively, oil can be directly applied to the stator end windings through nozzles, often through an oil distribution bar over the upper surface of the end winding. Both of these methods can have drawbacks; throwing oil off the rotor means that at zero or low speed the end windings are subjected to asymmetric oil cooling due to gravity. This leads to relatively higher temperature at the upper part of stator end windings as the copper loss component is substantial at stall and low speed operations. Also, applying oil to the end windings directly from the oil distribution bar can give a very uneven distribution of cooling around the radial periphery. Moreover, both oil spray cooling methods can lead to an additional windage loss if care is not being taken due to intrusion of oil into the rotor-stator gap.

![Figure 42 – Continuous torque characteristics](image)

4.4 Performance curves

A comparison of the continuous torque and power characteristics for the three cooling types is shown in Figure 42 and Figure 43. At lower speed the continuous torque capability is the highest with the oil spray cooling system, while the air cooling doesn’t give much improvement over the standard water jacket. However when the speed increases the effectiveness of the air-cooling system improves as the internal flow rate is related to the shaft speed.
4.5 Summary of cooling system comparison

We have introduced three different electric machine cooling mechanisms for an EV traction application. The water jacket is the least complicated approach and provides reasonably good cooling. The addition of internal circulating air adds additional components, such as the fan, however it may enable the use of lower grade magnets due to reduced rotor temperatures and result in overall cost saving. When compared to electrical losses, the windage loss caused by the fan is relatively small due to low density of air. This should have a minimal impact on the machine efficiency. The oil cooling adds quite a lot of complexity to the design however it also shows effective cooling and potentially simplifies the vehicle cooling system. Overall, the choice of cooling system is dependent on the required thermal performance, cost trade-off between components and the vehicle cooling system design.

5 Conclusion

In this paper we have considered a range of design decisions for electric machines in a battery electric vehicle. We have compared different motor types, winding technologies and cooling systems in terms of electric machine performance. We have also considered how these different design choices and performance attributes impact on the overall powertrain cost and performance.

During this study certain technologies have been shown to be advantageous however drawing generalised conclusions for the analysis is not necessarily helpful. Small variations in the specification and constraints can result in different conclusions and consequently different design decisions. System design, particularly when considering new powertrain and vehicle concepts, can be very iterative and many different topologies and design variants need to be considered during the system optimisation. As such using state-of-the-art software, such as Motor-CAD, allows these design variants to be studied quickly and easily enabling correct design decisions regarding the electric machine within an electric vehicle powertrain development process.

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