Next-generation integrated drive: A high power density permanent magnet synchronous drive with flooded stator cooling

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Abstract: The next-generation integrated drive (NGID) is an 80 kW demonstrator showcasing the latest innovations in high power density electric drive technology. A prototype 30 krpm maximum speed permanent magnet synchronous machine for an automotive traction application is under construction. This study describes several aspects of the detailed design and how these fit together in the complete drive package to increase the power density of the NGID.

1 Introduction

Internal combustion engine vehicles have been used for years in automotive applications; however, with low efficiency and high emission, the trend is moving towards battery electric and hybrid electric vehicles. The electric motors within these machines are efficient and have minimal impact on the environment. These motors must have a wide speed range, low cost, and fit within a limited space. To overcome these challenges, a lot of work has been done on permanent magnet (PM), induction, and switched reluctance motors [1, 2]. PM machines are the most common choice in automotive applications because of their high power density [3, 4]. Using strong rare earth magnets on the rotor, they can achieve high efficiencies due to having no excitation losses and very low rotor losses.

This paper shows that the power density of the PM machine can be improved further by integrating the power electronics with the machine. The machine is cooled by a flooded stator arrangement and the coolant is shared with the integrated converter. Integrated drives are of interest in applications where there is limited space for the drive and motor package, such as downhole pumping in the oil industry [5, 6]. However, recently there has been interest in this technology for other applications where space is at a premium, such as automotive and aerospace drives [7, 8].

2 Motor design

This paper presents the design of a motor to achieve the following torque and efficiency targets at two critical speeds, with the windings at 120°C and the magnets at 150°C: 76.4 N m, 95% at 10 krpm, and 25.4 N m, 97% at 30 krpm. The material used for both the stator and rotor laminations is JFE steel 10JNEX 900 with a thickness of 0.1 mm. The magnets are NdFeB with a residual flux density of 1 T at 150°C.

A surface-mounted PM (SMPM) machine was chosen to increase power factor, with a low pole number to keep the iron and switching losses low at higher speeds. The final slot–pole combination chosen was 9–6, which can be divided into three sub-machines and controlled separately to achieve fault tolerance. The machine was optimised at two speeds to achieve the target torque and efficiency values. The objective function of the machine was based on increasing efficiency while decreasing the volume of the machine.

Concentrated windings were chosen to reduce copper losses and improve torque density, thanks to short-end windings. The maximum current density chosen for the machine was 24 A mm⁻², achievable due to coolant in direct contact with the coils.

Magnet losses were found by using 3D finite element analysis (FEA) simulations. The magnets were axially segmented to reduce copper losses and improve torque density, thanks to short-end windings. The maximum current density chosen for the machine was 24 A mm⁻², achievable due to coolant in direct contact with the coils.

The dependency script shown in Fig. 1 was used to predict the current density >24 A mm⁻² all the solutions with the current density >24 A mm⁻². This script also set up the model for the optimisation run, confirming the current needed to achieve the target torque and setting this in the FEA model. Magnet losses and AC losses were found later after getting the best model from optimisation process (Fig. 2).

2.1 Optimisation

The motor was optimised using Infolytica Magnet Optinet software. A 2D finite element model of the motor is established, and simulated in the same way as expected within the real machine. Demagnetisation of the magnets and its effect on the torque were also investigated.

2.2 Interior PM machine

An interior PM (IPM) machine was investigated to check the potential for extra reluctance torque and to allow sensorless control due to the high q-axis inductance. A low pole number was chosen to keep the iron and switching losses low at higher speeds. The slot–pole combination chosen was 9–6. With this combination, the
machine can be divided into three sub-sections that can be controlled separately to achieve fault tolerance. Instead of distributed windings, concentrated windings were chosen to keep the copper losses low due to short-end windings, despite high torque density. The machine is likely to have mode 3 vibrations because of unbalanced magnetomotive force distribution [9].

The resultant model obtained from the optimisation process is shown in Fig. 3. The overall volume of the drive was estimated to be 4 l.

The IPM machine gives 20% extra reluctance torque at 30° electrical advance. Fig. 4 shows the torque at different advance angles.

Using the frozen permeability method, the power factor of the machine was found. The performance of the motor, such as output torque and power factor, depends on its two-axis inductances, $L_d$ and $L_q$. The power factor found from this method was 0.55 which is very low for a PM machine. Though more reluctance torque means higher power factor as the current moves towards the terminal voltage, the overall improvement is not significant.

2.3 SMPM machine

Having thoroughly investigated possible IPM machine designs, an SMPM machine was chosen to improve the power factor and efficiency while keeping the overall volume of the machine low. The air gap of the machine was increased to 3.65 mm to allow space for the stator and rotor sleeves. The stator and rotor pole numbers were kept the same. Fig. 5 shows the optimised machine structure.

To allow sensorless control to be used, saliency was introduced by adding steel between the magnets, increasing the q-axis inductance by 14%. Fig. 6 shows the q-axis flux with different steel thicknesses. The power factor was found to be 0.82.

Eddy current losses are generated inside the magnets because of the conductivity of NdFeB magnets and space harmonics, which can rapidly increase the temperature of the magnets [10–12]. Infolytica MagNet and JMAG FEA software were used to simulate the effect of segmentation of the magnets along the length of the rotor. It was found that using 1-mm long magnet segments reduced the losses by 95% compared with 10-mm long magnets. Fig. 7 shows the losses in the magnets with different segment lengths at 30 krpm. The final magnet stack length was chosen to be 1 mm as the rotor will not directly cool, and so the magnet losses must be minimised to keep the temperature within acceptable limits.

In high-speed machines, the AC losses are dominant because of the eddy current induced within the coil due to the high-frequency field generated by both the nearby coils and PM field flux (in PM machines) [13–15]. The conductors were carefully positioned within the slot and simulated in this arrangement to find accurate AC losses. The AC losses were calculated as 350 and 1200 W at 10 and 30 krpm, respectively. Fig. 8 shows the implementation of the conductor arrangement within the software simulation tool. The AC losses could be further reduced by using Litz wire; however, to
simplify the termination of the coils too, a single solid strand was
used.
Magnets are demagnetised when exposed to high temperatures
or high external magnetic fields. This affects the performance of
the machine especially in the constant torque region where more
electric energy will be required to achieve the required torque.
JMAG FEA software was used to examine this effect. Fig. 9 shows
in red the region of the magnet which is demagnetised at 10 krpm.
Fig. 10 shows the resultant torque of the machine at 10 krpm
after applying the reuse demagnetisation process. In this process,
the machine is rotated at a certain speed and demagnetisation
within the magnets due to high armature flux is observed. By
keeping the same magnet with its demagnetised regions as in the
previous simulation, the machine is rotated again at the same speed
and then the two torques are compared. The average torque
decreases by 0.9%.
The final motor design was simulated at the two critical
operating points specified previously. A breakdown of the losses
and calculated efficiency at these points is given in Table 1.

3 Mechanical integration
The drive housing plays an important role in the overall design of
the package. The high speed of the motor presents challenges in
maintaining an appropriate safety factor. The biggest challenge,
however, is to route the coolant through the housing, without
adding unnecessary restrictions which would result in a large pump
requirement. In spite of these issues, the housing must add minimal
weight and volume in order to maintain the high power density
concept.
This section describes how these obstacles have been overcome
to arrive at a feasible design.

3.1 Rotor retaining sleeve
Owing to the high rotational speed of the motor – 30 krpm
maximum with the design for 20% overspeed – the surface PMs
experience high centrifugal forces which the bond strength of the
adhesive used to affix them to the rotor core back is not sufficient
to withstand.
The solution to this is to use a retaining sleeve to hold the
magnets in place. As the sleeve is located in the air gap, its
thickness is critical to the electromagnetic performance of the
machine. It must be able to withstand the centrifugal forces from
the magnets and core back as well as its own hoop stress and
additional forces from thermal expansion.
Carbon fibre composite is the ideal material for this application
thanks to its high strength to weight ratio and will not cause an
extra loss due to induced eddy currents.
The sleeve was designed and manufactured by Arnold Magnetic
Technologies Ltd, a global leader in magnetic assemblies. A pre-
impregnated carbon fibre and epoxy tow composite material were
chosen. The sleeve was wound directly onto the rotor, which
requires less tooling than a pressed in place solution. The material
is wound under high tension to give residual hoop stress of 750
MPa at room temperature. This is the sum of the hoop stresses in
the sleeve due to the magnets and the sleeve itself, with a 2.95-mm
thick sleeve and a safety factor of 1.2. The resin is cured while the
sleeve is under tension, and so the epoxy is not under stress at

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**Table 1** Loss breakdown and efficiency at critical operating points

| speed, krpm | 10  | 30  |
|-------------|-----|-----|
| torque, N m | 76.4| 25.4|
| copper loss, W | 3468.4| 751.2|
| stator iron loss, W | 199.7| 416.8|
| rotor iron loss, W | 4.6| 3.5|
| total iron loss, W | 204.2| 420.3|
| magnet loss, W | 10.0| 30.0|
| AC loss, W | 305.0| 1200.0|
| total loss, kW | 3.99| 2.89|
| output power, kW | 80.0| 79.8|
| efficiency, % | 95.3| 96.6|
The presence of the stator and rotor sleeves in the ‘air’ gap (the sleeves are considered air from an electromagnetic perspective) and the need to maintain a physical air gap to account for tolerances in the component manufacture, bearings, thermal expansion, magnetic forces, and whirling, impose a minimum length on the air gap which affects the electromagnetic design.

Maintaining a physical air gap of 0.35 mm with the specified sleeve thicknesses results in a 3.65-mm electromagnetic air gap.

The effect on torque production of the variation in air gap length is assessed by FE simulation. The results are shown in Table 2 and show that there is a small but not insignificant effect on torque (and hence power) when the air gap is increased by 0.1 mm. There is also a very small decrease in the loss, and so overall, the effect on efficiency is minimal.

| Table 2 | Effect of varying air gap on performance at 10 krpm |
|---------|--------------------------------------------------|
| air gap, mm | 3.5   | 3.6   | 3.7   |
| torque, N m     | 76.83 | 75.75 | 74.68 |
| torque change     | 0.00% | -1.40% | -2.8% |
| output power, kW | 80.46 | 79.33 | 78.20 |
| efficiency, %     | 94.63 | 94.56 | 94.49 |
| efficiency change | 0.00% | -0.07% | -0.15% |

3.3 Impact of sleeves

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3.4 Winding design and stator assembly

The conductors are held in position within the slot to allow the coolant to flow past each and cool it effectively.

Each U-shaped turn of the 21-turn winding is pre-shaped on a former, and inserted individually into the slots, then terminated at the other end. The wire, with a nominal diameter of 1.18 mm, is bent around an aluminium form tool which has five different bend radii corresponding to the rows of turns in the slot. A second part of the form tool, made from polytetrafluoroethylene (PTFE) which is able to slide over the wire without damaging the insulation, presses the wire into the desired shape consistently. This tool is shown in Fig. 11.

3.5 Housing design

Apart from holding all the components together and protecting them from the external environment, while transmitting the torque produced to the mounting hardware, the housing must also contain the coolant to bring it into contact with the critical parts.

The key parts of the housing design are: the main cylindrical outer housing; the front end plate, which contains the front bearing; a power electronics plate, which locates the converter PCBs, directs coolant against the PCBs and down the slots, and seals the stator; a housing inner piece, which seals the rotor and shaft from the coolant; an rear end plate which holds the rear bearing and locates on the main housing, and also forms part of the coolant path; a presser, which transmits pressure from the end plate to the converter PCBs to secure them; and an inlet manifold, which connects the coolant path to the external cooling circuit and also holds the resolver.

Fig. 12 is an exploded view of the housing showing how the components fit together [from left to right: inlet manifold, rear end plate, inner piece, presser, power electronics plate, main housing (containing stator and rotor), and front end plate]. The path the coolant takes through the housing is shown in Fig. 13.

4 Conclusions

An SMPM machine for an 80 kW integrated drive has been designed. The machine has been optimised at two critical speeds to achieve the target efficiencies while reducing the overall volume of the drive. Based on the best model obtained from the optimisation, magnet losses and AC losses were found. The magnets were axially segmented to reduce the losses within the magnets due to harmonics. AC losses were found by assuming the copper temperature to be 60°C to consider the worst-case scenario of high conductivity and high eddy currents within each conductor. Reuse demagnetisation process was used to find the torque of the machine when a segment of the magnets get demagnetised. The results show only a 0.5% decrease in torque due to demagnetisation at the edges. Based on the output power and losses within the machine, the overall efficiency of the machine was found at 10 and 30 krpm, which was 95.5 and 96.6%, respectively.

The housing design allows the machine to be contained in the same physical package as the power electronic converter in a space-efficient way. The design of the common cooling system allows the high power density of the machine and converter designs to be realised in practice.
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6 References

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