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Development and Testing of a Low Cost High Performance Hybrid Vehicle Electric Motor

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ABSTRACT

A large proportion of automotive engineering research is focused on the reduction of vehicle fuel consumption thereby reducing CO_2 emissions. One effective method is to use an electric motor in conjunction with the engine (hybrid electric vehicle). This paper details the development and performance characteristics of a low cost hybrid vehicle electric motor, originally developed for the retrofit hybrid vehicle market, although it is intended to be suitable for many applications. The motor is a low cost, scalable, high performance motor, primarily for automotive applications. The motor has been designed to make it stackable for higher power or torque requirements. The use of lightweight materials and innovative cooling designs are novel to this motor. Results obtained from extensive testing of the motor are detailed in the paper including the efficiency map, power and torque curves, continuous powers etc. The peak torque obtained was 70Nm while the peak power output was 14.9KW, whilst the maximum efficiency of the motor was found to be in excess of 90%. It was also seen that increasing the magnetic air gap between the stator and the rotor from 1mm to 6mm, decreased the peak torque values of the motor from 70Nm to 45Nm, but helped achieve a higher speed of 7500rpm.

INTRODUCTION

Stringent emission standards and the need to adopt cleaner methods of transport have accelerated the use of electric motors in vehicles. Electric motors have the advantage of zero tailpipe emissions, reduction in noise and reduction in heat generation [1] [2]. There is an increase in the use of AC machines in the automotive industry over DC motors [3]. AC machines are broadly classified into two types, asynchronous and synchronous motors. Permanent magnet (synchronous) AC motors have become popular due to the steady state performance and also their high power density (output power to motor mass ratio), which is 30-40% more than a similar sized AC induction (asynchronous) motor [4]. They also tend to provide better dynamic performance and reliability when compared to squirrel cage machines [5]. Electric motors may also be classified as axial flux or radial flux, depending on the direction of magnetic flux lines inside them relative to the axis of rotation. In an axial flux machine, the magnetic force acts on the same plane as the shaft of the motor, whereas in the case of a traditional radial flux motor, it is perpendicular to the rotor shaft. Axial flux motors have higher power density when compared to radial flux motors and they are much more compact in construction [5]. Axial flux motors are comparatively thinner in size and thus have the nickname 'pancake motors'. They also provide better potential for mechanical field weakening by varying the air gap without much change in the overall efficiency of the motor compared to radial flux motors [6]. Increasing the air gap increases the copper loss as the torque constant reduces, which also reduces the iron losses, thus reducing the field density. This allows the motor to run up to higher speeds [6].

MOTOR CONSTRUCTION

The electric motor discussed here was designed by Ashwoods Automotive Ltd to be fitted onto light commercial vehicles to convert them into hybrid vehicles. It is an axial flux permanent magnet 3 phase AC motor fed from a traction inverter. One of the advantages of the motor compared to others is that it is very modular; most of the components can be bought off the shelf. In addition to this, use of rare earth magnetic material has been reduced compared to competitor motors of similar specifications, thus reducing the cost of production of the motor. Figure 1 shows the Ashwoods motor with the 3 phase power cables. The motor casing is 26cm in diameter and 10.3cm deep and the motor weighs approximately 19kg. The motor is designed to work in either static cooled, air cooled or liquid cooled conditions.

Figure 2 shows an exploded view of the Ashwoods motor. The rotor is made from steel and has laminated magnets bonded to it. There is a lightweight composite separation between the rotor magnets and the stator of the motor. The stator core is made up of powder iron, thus further reducing the cost and

Figure 1. Ashwoods axial flux 3 phase motor

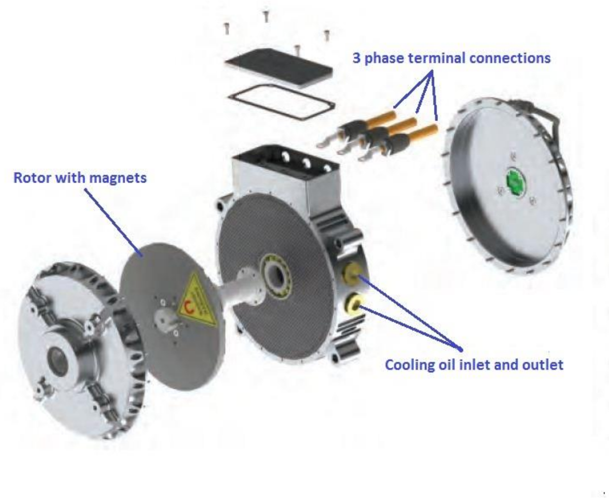

Figure 2. Exploded view of an Ashwoods motor

also the potential for eddy currents within the motor compared to conventional motor designs which use laminated steel [7]. An added feature of the motor discussed is its ability to be stacked with similar motors for high power and torque applications. The long rotor shaft and case accommodate for coupling of two or more motors to obtain the desired torque and power. The magnetic air gap was measured using a vernier caliper as the distance between the stator and the magnetic material on the rotors. This distance can be varied by adding shims of different thickness on the rotor shaft between the rotor and the stator.

TEST BED

The test bed consists of an axial flux double rotor motor, also produced by Ashwoods Automotive, acting as a dynamometer. This motor has two rotor assemblies, one on either side of the stator. The dynamometer is oil cooled and has a heat exchanger and two fans cooling the oil in case the motor reaches high operating temperatures. The motor has an oil cooling circuit that passes through various components in the motor like the shaft bearings, stator windings etc. This helps keep the operating temperatures at an optimum level for better performance and prevents the stator windings from overheating during high load operation of the motor. The test motor is connected to the dynamometer through a torque transducer and a speed sensor. There is a motor controller present at each end of the test bed for each of the motors. An 88V lead acid battery pack provides the DC power to run the motors. The battery pack is connected to both motor controllers creating an electric loop, with one controller inverting DC power and the other rectifying AC power by the use of MOSFET transistors. The dynamometer and the test motor can spin in either direction and both can act as a motor or a generator, achieving 4 quadrant operation. The electrical loop enables power to be fed back into the battery pack, thus there is minimum wastage of energy to run the test rig. A battery charger is used to top up the battery for the efficiency losses in the power transmission. Thermocouples are buried in each of the stator windings, rotor bearings and covers of both the motors. There is an oil reservoir with a pump to pass oil through the cooling circuit inside the motor. There is a separate battery and charger unit for the oil pump and radiator fans. Figure 3 shows the electric motor test facility at the University of Bath, UK.

The test rig is controlled by a computer running CP Engineering Cadet software. Various parameters like DC voltage, current, torque and temperatures are all logged by the computer, which can later be viewed in analysis software like Excel or Matlab.

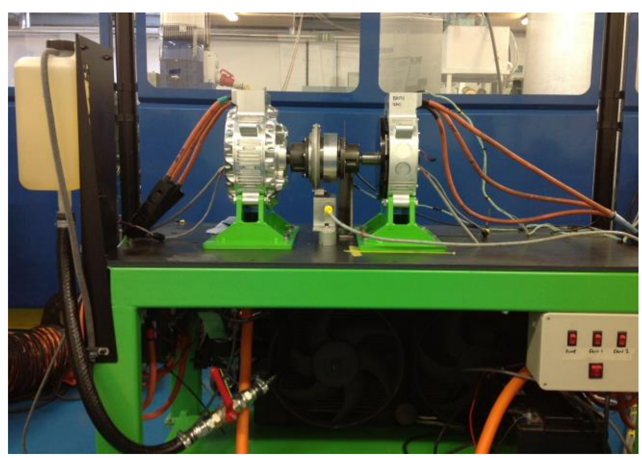

Figure 3. Electric motor test facility at the University of Bath

Table 1. – Ashwoods axial flux motor test results

Peak Power	14.9 kW
Peak Torque	70 Nm
Continuous Power	4.05 kW @ 2500 RPM
Continuous Torque	15.5 Nm @ 2500 RPM
Continuous Power (2mins)	12 kW @ 4000 RPM
Continuous Torque (2mins)	28.6 Nm @ 4000 RPM
Peak Efficiency	91%

TESTING AND RESULTS

The test procedure consisted of various steady state and transient tests ranging from maximum torque runs to continuous power and thermal performance of the motor. The first test consisted of the magnetic air gap being 1.2mm, which was the minimum possible due to the presence of a composite back plate present between the stator and the rotor. Table 1 shows some of the tested parameters in air cooled conditions. The peak power the motor attained was 14.9kW and the peak torque was 70Nm. The 3 phase windings of the motor had a maximum rating of $600A_{RMS}$. All the tests were conducted in a thermal window of 70-95ºC for the stator windings. Figure 4 shows the maximum torque and power curve of the motor. Continuous ratings were obtained by setting the motor to a speed and torque and ensuring the temperature gradient was no more than ±1ºC in 10 minutes. Motor efficiency is the output mechanical power of the motor divided by the AC power going into the motor. AC power was calculated by multiplying the measured DC power input to the inverter and the efficiency of the motor controller (96%) obtained from the manufacturer's data sheet. The mechanical power is product of torque and speed of the motor.

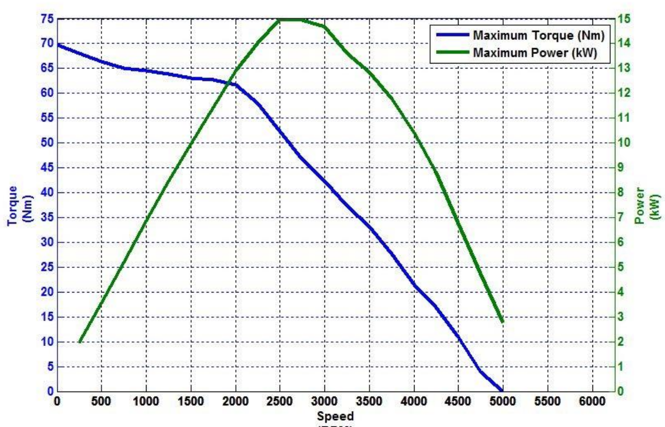

Figure 4. Maximum torque and power vs Speed of the motor (Magnetic air gap = 1.2mm)

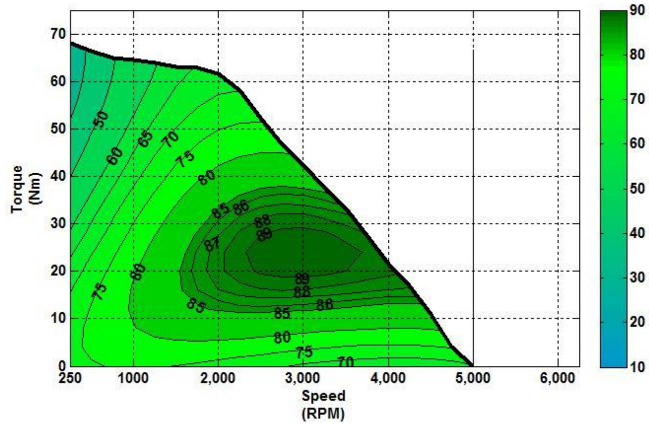

Figure 5. Efficiency map of Ashwoods axial flux motor (Magnetic air gap = 1.2mm)

$$Motor\ Efficiecny = \frac{Output\ mechanical\ power}{AC\ Input\ electrical\ power} * 100\%$$

Electric motors tend to provide highest torque at zero speed due to the absence of back EMF (electro motive force) which is evident in the plot. Maximum power of 14.9kW is in the region of 2500-2800rev/min.

For efficiency map testing, the motor was set to different speeds starting from stationary to the maximum speed in steps of 250rpm. At each speed interval, the torque was increased in steps of 5Nm and maintained for 5 seconds. The testing was carried out in static air conditions and in an operating envelope of 70-95ºC. The logged data was analysed using Matlab software and all the steady state points were selected and fed into Model Based Calibration toolbox to generate an efficiency map. The efficiency map generated from the data was seen to have a goodness of fit (R^2) value of 0.97. Figure 5 shows the efficiency map for the axial flux motor with a magnetic air gap of 1.2mm. The efficiency map is bordered by the limiting torque of the motor. The map shows the most efficient region of the motor is 2250-3750rpm with the efficiency being greater than 90%. The low efficiency regions are the low speed high load conditions where temperature of the windings rapidly increased due to the amount of current being passed through the coils.

An electric motor's maximum speed is governed by the back EMF it generates. Back EMF is the voltage developed in the windings of the stator due the presence of rotational magnetic field around it. One of the methods to reduce the back EMF is to increase the magnetic air gap between the stator coils and the rotor of the motor. This reduces the flux density, thus reducing the back EMF of the motor. Increasing the air gap allows the motor to achieve a higher maximum speed. This procedure sacrifices peak torque values of the motor, due to the reduction in flux density. For the next stage of testing, the magnetic air gap was varied by adding shims between the

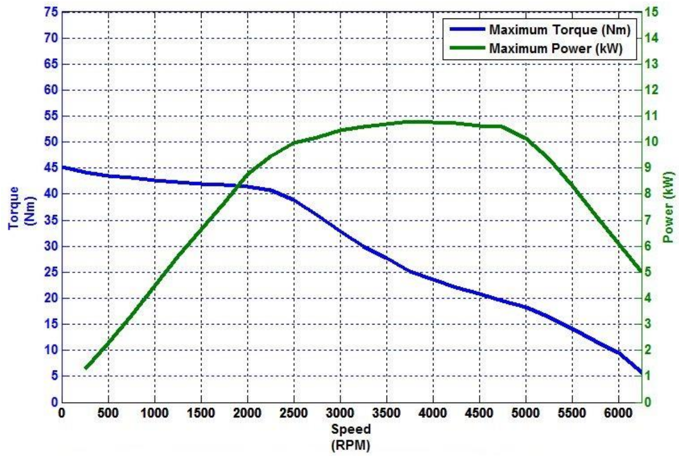

Figure 6. Maximum torque and power vs Speed of the motor (Magnetic air gap = 6mm)

stator and the rotor on the central shaft of the motor. The air gap was increased from 1.2mm to 6mm to observe the change in key parameters. Only peak torque and efficiency map runs were carried out for this condition.

Figure 6 shows the maximum torque and power curves of the motor with a magnetic air gap of 6mm. It can be seen that peak torque has dropped from 70Nm to 45Nm. This is due to the reduction in flux density as a result of the increased magnetic air gap. The maximum speed of the motor increased from 5000rpm for 1.2mm air gap to 7500rpm for 6mm air gap. Thus changing the air gap from 1.2mm to 6mm provided a 35.7% reduction in peak torque, but provided a 50% increase in the maximum speed of the motor. Previous studies have shown that this process is possible without sacrificing high efficiency regions [6].

One of the other interesting findings was the presence of a

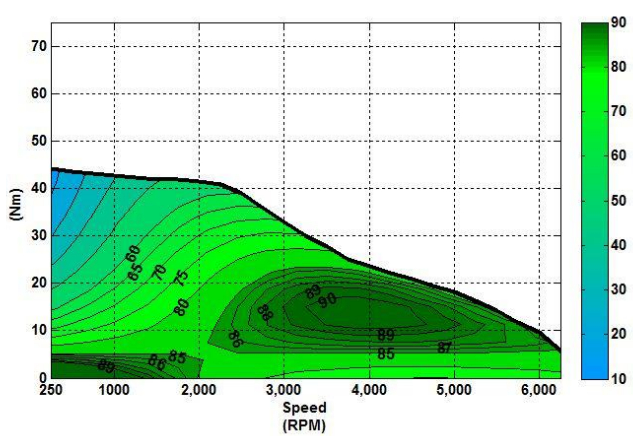

Figure 7. Efficiency map for the axial flux motor (Magnetic air gap = 6mm)

broader (flatter) maximum power. This is particularly beneficial at higher speeds as the electric motor is capable of delivering higher powers at speeds 4000rpm. An electric motor with a wide maximum power band can prove to be useful for various off highway applications.

Figure 7 shows the efficiency map of the axial flux motor with the increased magnetic air gap. The map is scaled to the same as the previous efficiency map. The maximum efficiency of this case was found to be the same as the previous case - 91%. However, the high efficiency regions are seen to be more prominent and cover a larger speed and torque range. It was observed that the thermal performance of the motor at moderate and high speeds was better than when it was tested with 1.2mm air gap. The stator windings tended to heat up slower than at a low air gap setting. Another interesting phenomenon that can be seen in the efficiency map is the presence of a high efficiency region in the low speed low load conditions. This may be due to the reduction in back EMF as a result of increase in the magnetic air gap between the stator and the rotor. The increase in magnetic air gap not only yielded an increase in the maximum speed of the motor, but also provides a high efficiency region in this speed region.

CONCLUSIONS

A low cost axial flux 3 phase motor was tested and various key performance parameters were identified. Various innovative features like a cooling circuit through the stator coils and the use of lightweight composite materials make the motor a novel design. The use of powder iron material for stator core and the modular construction of the motor help reduce its cost, placing it ahead of its competitors. The motor's design also makes it stackable, making it flexible for two or more motors to be coupled together and used for high power or torque requirements.

The magnetic air gap, which is the distance between the stator and the rotor of the motor, was changed from 1.2mm to 6mm. This allowed the motor to run up to a maximum speed of 7500rpm, achieving higher torques at high speed, but sacrificing peak torque values. It was also noted that there was a considerable increase in the spread of the high efficiency (85%+) regions compared to the lower air gap. There was also a high efficiency region at speeds below 2000rpm low load conditions. From the plots it can be seen that the motor is efficient over a wide range of speed and power (2200-6000rpm), reducing the need to gear it when fitted onto a vehicle. Further testing is required to properly understand the reasons for the increased efficiency for the large air gap condition. Future work also involves the development of a mechanically varying air gap motor. This would reduce the need for a multi-speed transmission, as the air gap could be varied to make use of the best features of each setup: high maximum torque during transients, with a wide speed range and large region of high efficiency in steady state operation.

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