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Test and Simulation of Variable Air Gap Concept on Axial Flux Electric Motor

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Abstract—One of the most promising methods to reduce vehicle fuel consumption and CO₂ emissions is by using an electric motor in the vehicle powertrain system to assist the internal combustion engine, or propel vehicle by itself. This paper discusses a new potential method to improve axial flux motor performance and efficiency, by dynamically changing the air gap between the rotor and the stator. A series of experiments have provided insight into how certain key characteristics of the variable air gap (VAG) across a wide range of air gap settings. The results show that, on increasing the air gap from the normal 1.2mm to as much as 18mm, the peak torque reduces from 72Nm to 16Nm while the maximum speed of the motor increases from 5500rev/min to over 7000rev/min. It was seen that the high efficiency region moves towards the higher speed region as the air gap increases. Also, on increasing the air gap, the motor had a higher torque output at high speed. This behaviour is of limited benefit in a fixed geometry design, but the implementation of a software controlled air gap design allows the motor characteristics to be varied to suit the prevailing operating conditions. To demonstrate this benefit, the experimental data were used to build a model of the motor with a dynamically variable air gap concept incorporated into it. This model was then used with a fixed ratio powertrain, combined with a simple vehicle model and exercised over the NEDC drive cycle to predict the savings it would achieve when compared to a standard electric motor of similar technical specifications. The model predicts the overall battery energy usage reduced by 0.72% when using a VAG design. In addition, the VAG concept has the potential to reduce gearbox complexity and provide better drivability at higher speeds over the standard motor.

Keywords—Axial flux; permanent magnet motor; traction motor; variable air gap; electric drive; hybrid electric vehicle; HEV; electric vehicle; EV; motor simulation.

I. INTRODUCTION

In recent years, rise in the price of oil and strict vehicle emission standards have made the use of electric motors in automotive applications a subject of increasing attention. Efficiency is highly important for traction motors when the total on-board battery capacity is restricted. Improving the trade-off between cost and efficiency is crucial to the commercial viability for hybrid electric vehicles (HEV) and electric vehicles (EV).

A few different types of electric motor for vehicle propulsion systems have been proposed and tested. Among these solutions, the permanent magnet (PM) synchronous motor is more favored by automotive engineers [1]. With the presence of permanent magnets in the rotor, the current in the stator is only for torque production. Consequently, when comparing with the induction motor, PM motors are able to operate with a higher power factor since there is no need for magnetizing current, thus making them more efficient [2]. At high load conditions, synchronous operation could limit the rotor loss. Besides, since stator current is relatively low in brushless motor, a relatively cheap inverter is needed for PM motors, which is another reason for its popularity [4].

On the basis of the magnet flux orientation against the rotating shaft, the PM motor is classified in two groups, axial and radial flux geometries. The former style has an inherent advantage in volume when compared to the latter one. The ‘pancake’ shaped stator can have a disk rotor attached on one or both sides. Unlike the radial flux motor, in which part of the rotor centre core volume does not really contribute to the power generation, an axial flux PM motor internal structure lends itself to achieving higher power density [3]. In addition, axial flux motors have the option of mechanically varying the distance between stator and rotor, thus inducing mechanical field weakening, which is not possible in the case of radial flux machines. The easily adjustable air gap suggests that the axial flux PM motor could exhibit better dynamic performance and improved overall efficiency. The air gap is a key factor in motor design since it will define the motor speed and torque output characteristics. A small air gap allows less flux leakage, which helps improve the peak torque output. When the air gap is increased, the torque constant will decrease allowing the motor be able to spin at a greater speed range. Dynamically changing the air gap offers an effective way to access both high torque and high speed from one motor, to adapt to various driving scenarios.

In this paper, an axial flux permanent magnet motor designed for hybrid vehicle powertrains is tested with different air gaps. The efficiency of the traction motor is mapped for each air gap. The authors had previously tested the motor and varied the air gap to demonstrate the technology [6]. A simulation model based on the test data has been created and used to determine the optimum air gap for each motor

operation point. Then, the dynamic variable air gap (VAG) motor model was combined with a simple control strategy for choosing optimum operation points and exercised over a simulated New European Drive Cycle (NEDC). The results are compared to predictions using a fixed air gap motor over the same duty cycle.

II. MOTOR TEST

A. Test motor specifications

The test motor is designed and manufactured by Ashwoods Automotive Ltd for a retro-fit light commercial hybrid vehicle powertrain. It is a 3-phase axial flux permanent magnet synchronous motor which is designed to be stackable. Multiple motors could operate on the same shaft to deliver required torque/power [6]. The motor specifications are shown in TABLE I. The factory setting for the air gap is 1.2mm.

TABLE I TEST MOTOR SPECIFICATIONS

Rated voltage	72 V
Peak power	14.9 kW
Peak Torque	72 Nm
Max Speed	5500 RPM
Peak efficiency	>90%
Continuous power	4.05 kW
Cooling	Air cooling
Weight	~19Kg
Dimensions	Ø234mm*130mm
Magnet pole pairs	5

B. Test bench setup

The dynamometer is a dual-rotor axial flux permanent magnet motor, manufactured by Ashwoods Automotive. The stator's internal components (including windings, bearings, etc.) are oil cooled by an external pump to provide more stable performance. The test motor and the dynamometer are directly connected through a torque sensing flange. A speed transducer is connected between the motors. Both motors have individual MOSFET inverter controllers, and draw power from a common lead acid battery pack. The arrangement creates a closed electric power loop which restores energy from the driven motor to the battery. The losses are topped up using a mains driven charger. Since both motors are connected to the same power source, the battery voltage level is not easy to hold constant during operation. However, a previous study shows the motor efficiency is only affected slightly when varying DC supply voltage [5]. Motor parameters such as temperature, speed, torque, voltage, current, etc. are acquired by Sierra CP Engineering Cadet software and logged for analysis.

As the simulation involves a tractive application, the experimental test was done in the first quadrant. However, the motor is capable of operating in all four quadrants. The motor controller efficiency was assumed to be 96%, which is claimed by the manufacturer. The same drive was used for all tests and so uncertainty over controller efficiency applies equally to both the VAG and fixed configurations. The motor efficiency mentioned in this paper refers to the drive mode efficiency only. The motor 1st quadrant efficiency is calculated as

$$\text{efficiency} = \frac{2\pi \times \text{motortorque(Nm)} \times \text{motorspeed(rpm)} / 60}{\text{DCvoltage(V)} \times \text{DCcurrent(A)} \times 0.96} \quad (1)$$

C. Test procedure

The dynamometer is under speed control while the test motor is in torque control. During the test, the dynamometer motor is spun and held at the required speed. Then, a torque is applied by the test motor by varying the stator current. The torque is increased in steps of 5Nm. A five-second average is taken for all motor parameters at each torque point. After all the points are finished for one speed, the dynamometer is set to the next speed. The test starts from 250rpm, and speed is increased in steps of 250rpm. To keep the motor working condition consistent, tests are carried out in a thermal window of 70 to 95 Celsius, which is defined as the motor operating temperature by the manufacturer. The motor runs with 1.2mm air gap at the beginning, which is measured from rotor magnet surface to the stator windings. Then, the air gap was manually changed between tests, by adding shims to the shaft collar which supports the rotor. The air gap is increased in increments of 0.5mm.

D. Test results

All the steady state data was analyzed in the Matlab environment, and used to build motor efficiency models for each air gap, using the Model Based Calibration Toolbox.

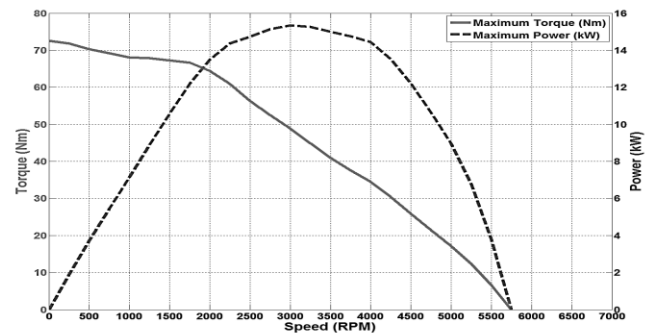


Fig. 1. Torque-power envelop for 1.2mm air gap

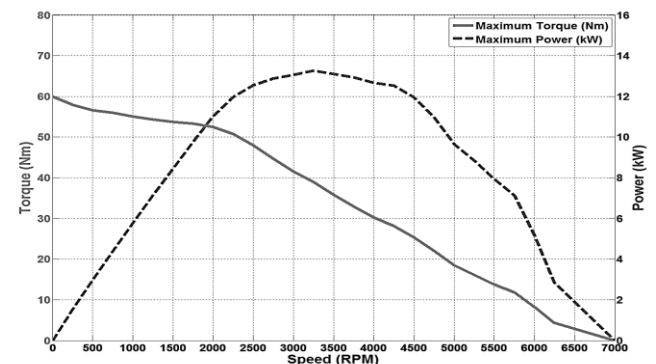


Fig. 2. Torque-power envelop for 3.1mm air gap

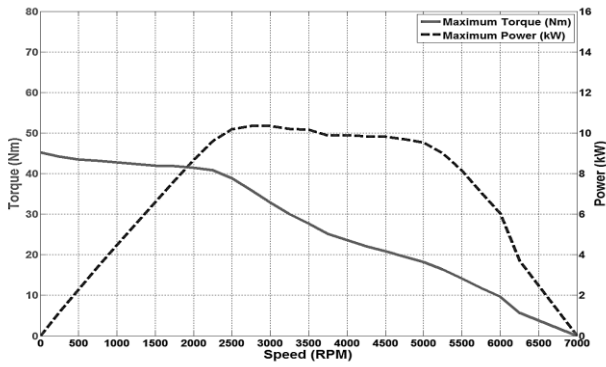


Fig. 3. Torque-power envelop for 6.0mm air gap

From these plots (Fig. 1-Fig. 3), it can be seen that, the minimum air gap of 1.2mm provides highest torque when compared to any other air gap. However, the maximum speed achieved by the motor in this condition is only 5500rpm, with no amount of torque being produced. When the field is mechanically weakened by increasing the air gap (say 6mm), the motor is able to produce 5.3Nm torque even at 6250rpm, and the maximum speed has increased to 7200rpm. It can also be seen that a flatter peak power band is obtained when compared to the same in small air gap condition.

It can be seen in the efficiency maps (Fig. 4-Fig. 6) that the change in air gap does not affect the motor's peak efficiency significantly. It drops from 94% to 89%. The high efficiency island shows a clear movement from low speed to high speed region when the air gap is increased. As the torque profile varies along with the air gap, the shape of high efficiency area is compressed and stretched from nearly round to narrow ellipse. This allows the motor to work in a highly efficient operation condition in larger speed boundary.

These results give the indication that dynamically changing the air gap gives the potential of improving the motor performance and efficiency at the same time.

III. VAG MOTOR MODELLING

With real test data for a series of air gaps, a preliminary simulation model of a motor adopting the variable air gap concept was developed. The core of the model is an air gap controller which chooses the optimal air gap for current speed and torque demands with respect to motor efficiency. In defining this optimum condition, the efficiency, defined as the ratio between output mechanical power and input electric power, is maximized for each operating point. To this end, a database containing all the efficiency information based on the real test data was generated. For each operating point (every air gap, motor speed and torque combination), the 3D lookup table is able to output a motor efficiency value. Boundary conditions were set to avoid the model extrapolating outside the working envelope of the motor. Fig. 7 shows the boundary model for motor efficiency throughout all air gaps. The air gap range was set to range from 1mm to 24mm.

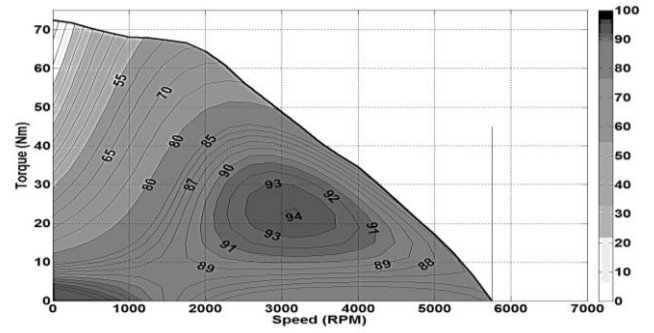


Fig. 4. Motor efficiency map for 1.2mm air gap

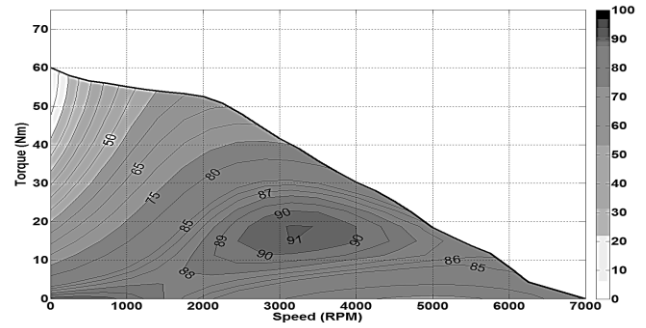


Fig. 5. Motor efficiency map for 3.1mm air gap

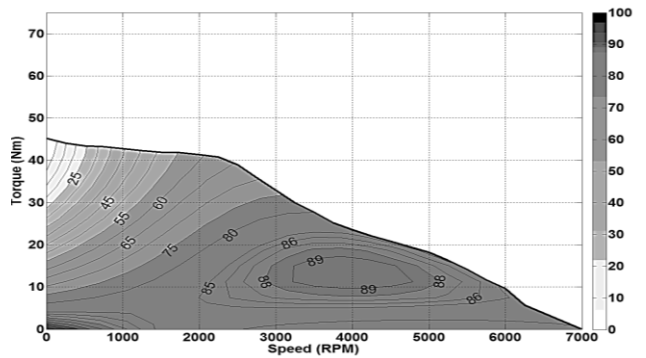


Fig. 6. Motor efficiency map for 6.0mm air gap

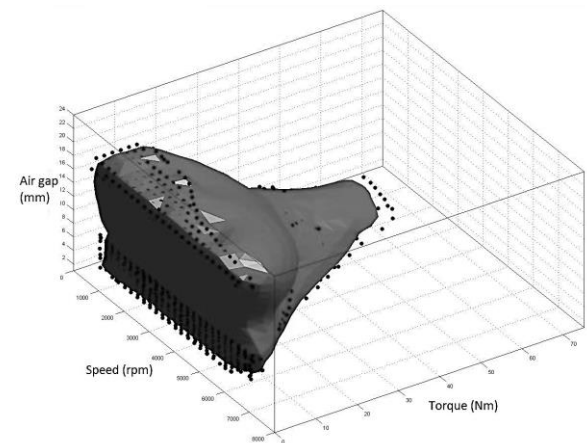


Fig. 7. VAG efficiency boundary model

By referring to the motor efficiency model, the air gap controller is able to select the optimal air gap, which permits the motor to work at best efficiency at required speed and torque demand. Fig. 8 shows the optimal air gap at a range of loads throughout the speed range, and Fig. 9 shows the corresponding efficiency curves at these optimal air gap values. In the plots, the air gap is enlarged at either end of these curves which means that changing the air gap improves the efficiency at low speed and extends the operating range of the motor at high speed. Otherwise the controller keeps the air gap relatively small to give similar performance to the fixed geometry motor. In all load cases motor efficiency increases with speed and reaches maximum at around 3000rpm.

Motor speed and torque demand are the inputs to the air gap controller strategy in the VAG motor model. The controller processes these inputs and provides the actual output torque to the gearbox and also the system efficiency at that point.

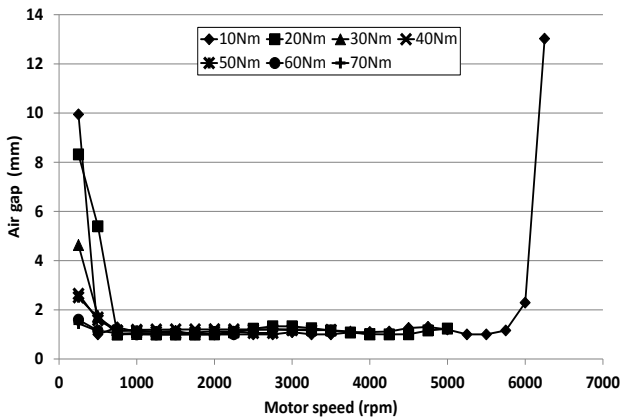


Fig. 8. Optimal air gap curves at a range of loads

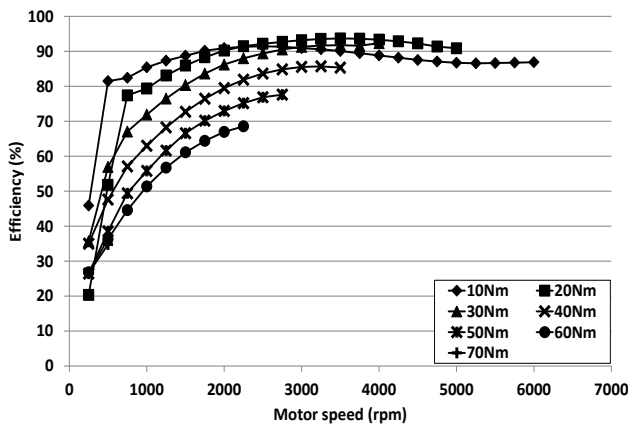


Fig. 9. Optimal air gap efficiency at a range of loads

IV. DRIVE CYCLE SIMULATION

In order to study the theoretical effectiveness of the VAG concept, the VAG motor is compared with a constant air gap (CAG) motor (standard Ashwoods motor) under The New European Drive Cycle (NEDC) which includes four urban drive cycles and one extra-urban drive cycle. A model for the CAG motor was first created using test data collected from

1.2mm air gap. The only difference in the model between VAG motor is the lack of the air gap selection mechanism.

Road load and vehicle configuration data measured from an unmodified Ford Transit van was used to represent the target vehicle in the simulation. Since the motor is designed to be stackable, five motors are connected on the same shaft allowing the traction unit to meet the torque and power requirements in the NEDC. The desired speed and torque to the final drive are shown in Fig. 10, which are calculated from an ideal NEDC cycle for the target vehicle. In the following analysis, the motor’s performance in urban drive cycle and extra-urban drive cycle is studied separately when necessary.

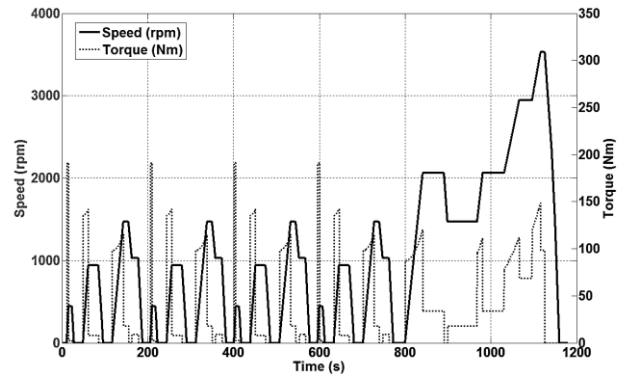


Fig. 10. Post-gearbox speed and torque in ideal NEDC for Ford Transit

As mentioned in the previous section, the lowest speed and load represented in the data set is 5Nm and 250 rpm. This is due to the wide measuring range required of the instruments, which makes data acquisition at extremely low torque and speed inaccurate. However, low speed and torque demand does exist in the drive cycle, during vehicle pull-away and constant speed cruising. To avoid improper extrapolation from the model resulting in invalid torque and efficiency predictions, all running points outside the boundary model are excluded in the later analysis. Fig. 11 shows the position of these barred points. The mechanical energy consumed at these invalid points takes up to 8.32% of the total amount.

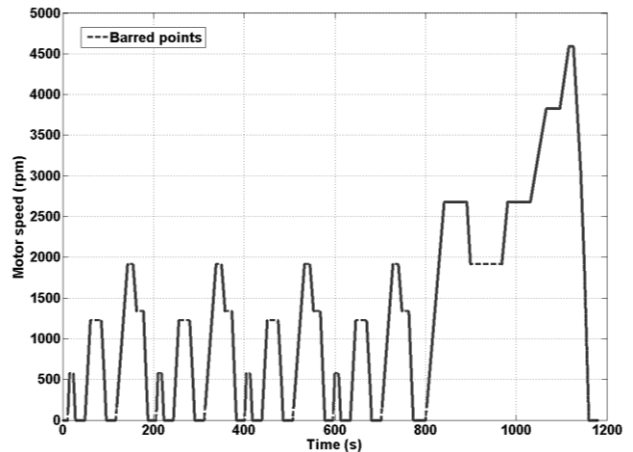


Fig. 11. Barred points in NEDC for the model

A single speed gear box is designated to be used for two types of motors. However, due to the motors' different speed and torque characteristics, to be able to complete NEDC a common gear ratio is not suitable for both. The maximum gear ratio available for the VAG motor is 1.4:1, while 1.3:1 is for CAG motor. Fig. 12 and Fig. 13 show how the average motor efficiency over the urban and extra-urban phases of the cycle changes as a function of gear ratio. TABLE II gives the most efficient gear ratio for the two motors in both sub drive cycles. In the simulation, the change in efficiency of the gearbox with load and temperature is not considered, and has been simplified to a constant 95% through its speed and torque range.

TABLE II MOST EFFICIENT GEAR RATIO

Drive cycle	Gear ratio (motor efficiency)	
	VAG	CAG
Urban	1.4 (79.3%)	1.4 (72%)
Extra-urban	1.4 (87.2%)	0.9 (89.2%)

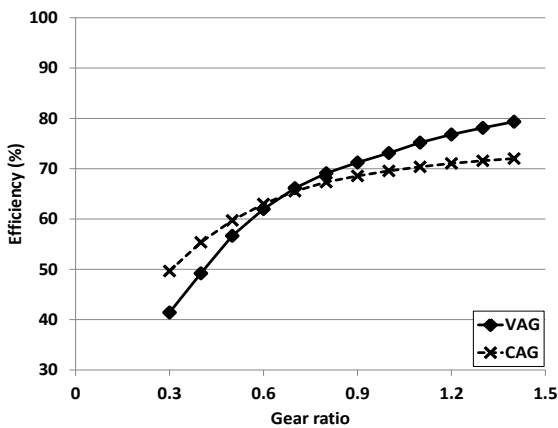


Fig. 12. Motor efficiency in urban drive cycle

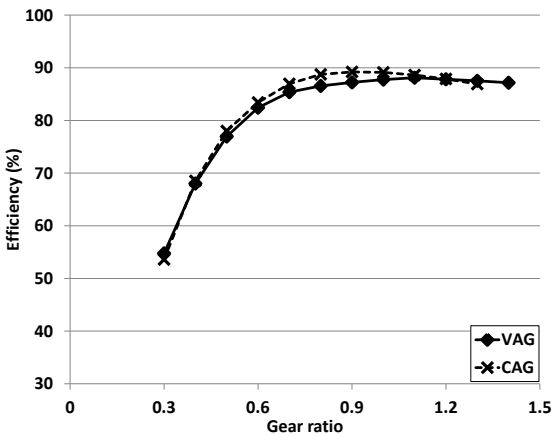


Fig. 13. Motor efficiency in extra-urban drive cycle

The results show that a single speed gearbox is sufficient for the VAG motor working in high efficiency through the entire drive cycle. However, to keep the CAG motor operation in the optimal conditions and be able to finish the whole drive cycle, a multiple-speed gearbox is needed. This indicates the

potential that the VAG concept helps reduce the complexity of gearbox design.

Fig. 14 shows the air gap and motor speed in the urban and extra-urban drive cycles in the NEDC. During the acceleration phase, a high torque is required. The VAG controller thus sets the preferred air gap to the minimum condition to provide sufficient traction force. Due to this reason, the two types of motor show similar efficiency and performance during this phase. However, once the vehicle is in a moderate speed cruise, the air gap controller increases the air gap to a more efficient point, as the VAG motor is more efficient than the CAG motor in this region. In extra-urban drive cycle, since the motor has to operate at its limit for high speed acceleration and cruise, VAG works mostly in small air gap. To acquire the maximum benefits of energy regeneration and motor braking, the air gap is designated to be as close to the minimum as possible, when braking or coasting.

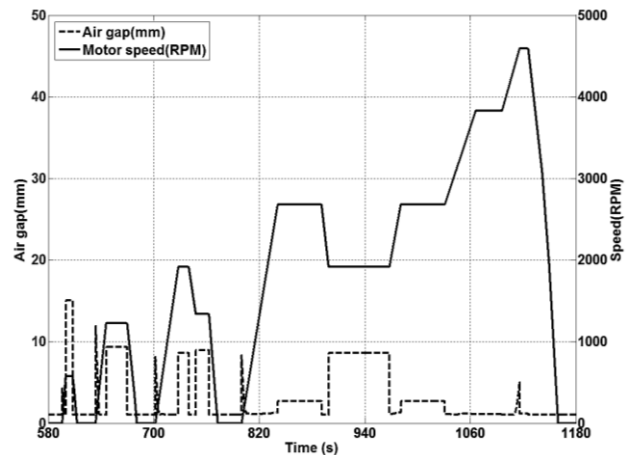


Fig. 14. Air gap change in the last two sub drive cycles of NEDC

Fig. 15 shows the maximum torque profile for CAG and VAG motors. From zero speed to 4500rpm (corresponding vehicle speed is 117.5 km/h), the two curves coincide which means the peak torque is provide at minimum air gap. After this point, enlarging the air gap helps the motor achieve a higher value of torque at higher speeds, which provides better drivability. The dotted line in the figure is the road-load curve, defined as the minimum torque needed for the target vehicle travelling at a constant speed. The intersection points of the motor limiting torque curves and the road load curve indicate the theoretical maximum driving speeds that can be achieved by the two designs. When fitting the same single speed gear ratio, the vehicle has a higher top speed with the VAG motor. This benefit was seen in the simulation results. Both motors are fitted with a gearbox with 1.3:1 ratio for this comparison in order to allow both types of motors to complete all sections of the drive cycle with a common gear ratio. In addition, this ratio provides a compromise between high speed performance and efficiency for both motors. A useful calculation is the torque margin, defined here as the extra torque available from the motor over and above that needed at any point in time to follow the target speed vector. This can be calculated at all points in the drive cycle and interpreted as a drivability attribute, specifically a measure of potential performance increase

available to cater for driver demand changes in real world situations. In the urban drive cycle, the torque margin curves from two types of motors overlaps since the speed never exceeds 2000 rpm. But in the extreme high speed region of the extra-urban drive cycle, the torque gain of VAG is evident (one example shown in Fig. 16). The higher the gear ratio, the more prominent is the torque advantage at higher speeds.

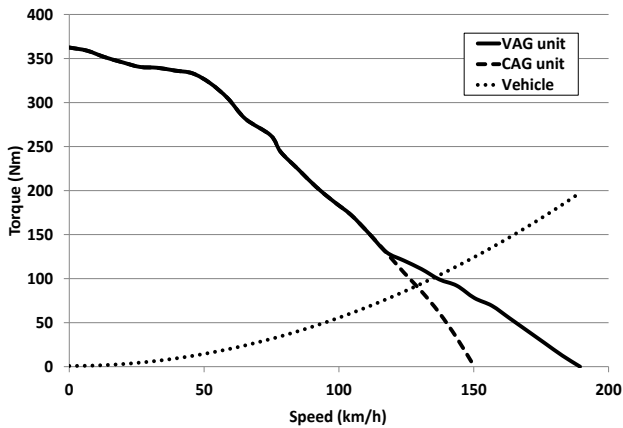


Fig. 15. Minimum driving torque for Transit and maximum torque profiles for VAG and CAG motors

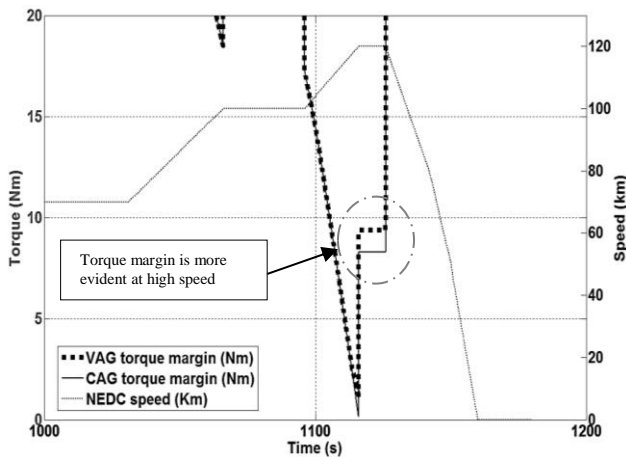


Fig. 16. Torque margin at high speed region in NEDC

The overall simulation results are shown in TABLE III. The VAG motor gives a better average efficiency over CAG. The battery energy consumed during the drive cycle can be calculated using the motor mechanical output and instantaneous efficiency. The result shows that the VAG motor saves 0.72% of the total electric energy over the CAG design. In doing so, the VAG design reduces the gearbox complexity and helps achieve higher motor speed without compromising the performance and efficiency.

TABLE III OVERALL VALID TEST POINT RESULTS

	Avg. motor efficiency	Battery energy saved
CAG	86.75%	-
VAG	87.07%	0.72%

V. CONCLUSION

In this paper, an axial flux motor was tested in the 1st quadrant with a range of air gap settings. The results indicate that by enlarging the air gap, the motor is able to spin faster (max speed increased from 5500rpm to 7000rpm) and the high efficiency region moves towards high speed region. This provides the motor a larger envelope to operate more efficiently. The test data collected was used to build a VAG motor model capable of determining the optimal air gap for a speed and torque demand, based on efficiency of the motor. This model was simulated on the NEDC with ideal speed and torque demand data set, based on a five motor stacked configuration, targeted at a standard Ford Transit vehicle. The simulation results showed that a higher efficiency is obtained by varying the air gap in the moderate to high speed cruise sections of the cycle. The battery energy saving for whole NEDC is improved by 0.72%. During high speed driving, better drivability is provided by offering a higher torque margin from the VAG. The VAG concept also reduces the dependence on a multi-speed gearbox since both high speed and high torque are accessible within motor itself.

Future work involves development of the variable air gap actuation system model by including more motor test data in the low speed and low torque range and taking into account the efficiency of the motor controller based on load, rather than assuming a constant value. The next phase of the work involves testing the motor in all four quadrants to model the regenerative capability of the motor and also its ability to work efficiently in reverse direction. With regards to modeling, the air gap variation dynamics need to be measured experimentally and modeled correctly.

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