Lightweight, Highly Efficient Drive System

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This paper presents a joint project conducted by Ashwoods Electric Motors and Oerlikon Fairfield that uses planetary drives with an integrated electric motor. Current solutions used in production of off-highway vehicles rely upon large, heavy and inefficient brushed DC or induction motors, coupled to a planetary gearbox. This presents a number of challenges to the vehicle designers such as: limited vehicle range, limited space around the motor/drivetrain, and motor durability. The proposed integrated system utilizes an Oerlikon Fairfield Torque Hub, widely used in off-highway vehicles, and the Ashwoods first-to-market, interior permanent magnet motor. How these products are integrated, i.e. — incorporating a brake solution — represents a market-changing product. Using interior permanent magnet (IPM) technology in the motor design means the motor can be up to 70% lighter, 70% smaller and 20% more efficient than traditional motors used in off-highway traction applications.

Introduction

Planetary gearboxes are widely used in material handling and off-highway applications. Many of these applications incorporate hydraulic motors into the planetary gearbox, but the solution discussed in this paper utilizes an electric motor for the same tasks. The gearbox used is a planetary drive manufactured by Oerlikon Fairfield under the Torque Hub name. The electric motor is an interior permanent magnet electric motor manufactured by Ashwoods Electric Motors.

The paper will outline the solution proposed by Oerlikon Fairfield and Ashwoods Electric Motors, and discuss integration of the components. Comparisons are made with the existing electric/hydraulic motor technologies typically used to drive planetary gearboxes. Alongside the performance of the solution, the testing and validation plan is also discussed.

Applications suited to the proposed solution are identified and discussed, demonstrating the feasibility of utilizing this solution within the application.

The performance of the current configuration of the planetary gearbox and electric motor is outlined in Table 1, and future models are discussed in the paper.

Table 1 48V performance

The values below are for a 48V system with a Single Core IPM motor and a 96.15:1 Ratio	
Weight	76kg
Size (Dia × Length)	293 x 408 mm
Max Output Torque	3846 Nm
Max Braking Torque	4807.5 Nm
Max Power	9kW
Max Output Speed	62RPM
Regeneration	Full regeneration capability
IP Rating	Designed to IP65
Braking	Electric parking/emergency brake

Figure 1 Ashwoods and Fairfield solution.

Interior Permanent Magnet Motor Technology

An IPM motor has the capability of combining both reluctance and permanent magnet motor technology. Permanent magnet motors are well known for their high torque density, achieved largely due to the high airgap flux density produced by rare earth magnets. A reluctance motor is able to produce torque without the use of magnets. Combining the two technologies produces an interior permanent magnet motor that provides a similar torque density to an equivalent permanent magnet motor, but with up to 70% less magnet material. This can have a dramatic effect on motor cost; Figure 2 is a simple image displaying the fundamental attributes of an IPM motor.

The results produced by the characteristics mentioned above mean that an IPM motor can be up to a third of the size and weight of an induction or brushed DC motor, while staying cost-neutral or cheaper for a given power rating. It can also have performance benefits such as a high efficiency that accompanies permanent magnet motors. Yes, many IPM motor manufacturers still charge a large premium for their products, but these motors are usually highly optimized with exceptionally good performance results. Ashwoods has scaled their IPM motors from the high-performance models used in many automotive applications and targeted the cost-competitive off-highway and material handling markets with them. This approach has given a motor that is cost-competitive with traditional motor technology while offering all the benefits of permanent magnet technology.

In many applications a motor's location means it is unsprung mass and exposed to harsh vibrations; this can cause insulation failures within the motor. The Ashwoods IPM motor incorporates encapsulated windings and stator to protect the motor against vibration fatigue. It also means the windings are not exposed to environmental conditions.

The identity of an IPM motor means the magnets are embedded within the rotor design. This eliminates risk of a magnet separating from the rotor and causing failure; it also allows the rotor to rotate at higher speeds. In addition to the windings, the magnets can be completely encapsulated, thus protecting them from environmental and vibration fatigue.

Typically, an IPM motor is low in volume and lightweight. This means the motor core does not provide a large heat-sink to distribute the losses created within the machine. Thus an intelligent cooling/air circulating design is required to provide the motor with high, continuous power. This is something Ashwoods has developed and, as a result, has produced a motor that can produce up to 70% of its peak power as an S1-rated (continuous) power.

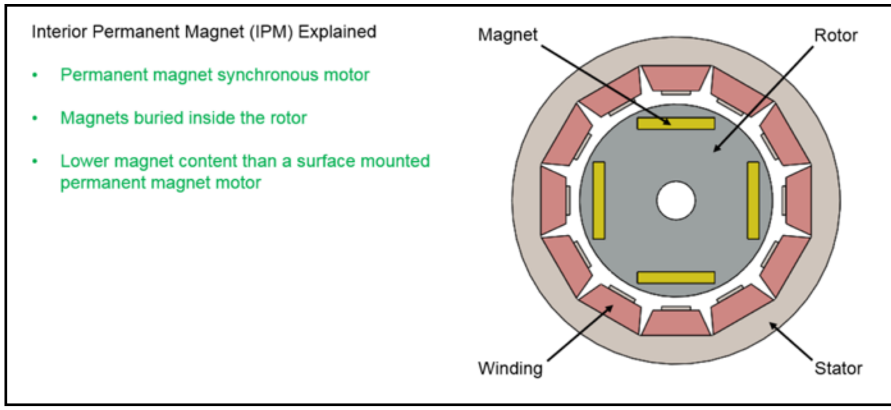

Figure 2 **Interior permanent magnet explanation.**

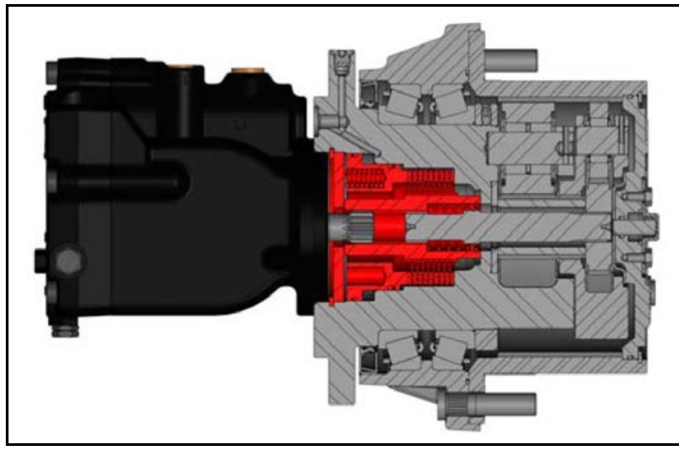

Figure 3 **Two-stage gearbox with hydraulic motor.**

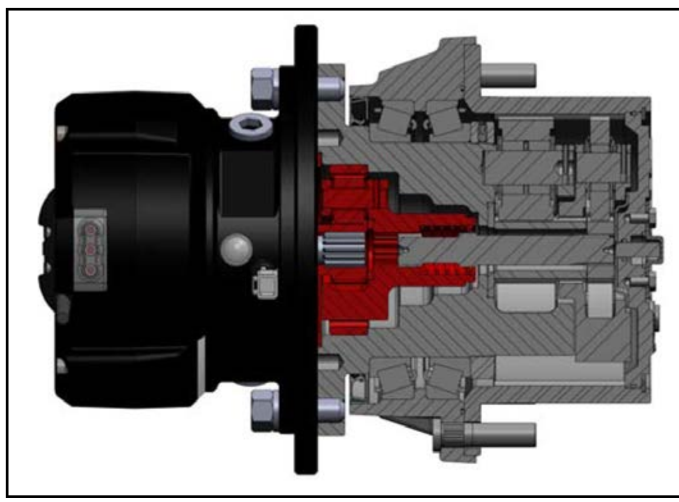

Figure 4 **Three-stage gearbox with IPM electric motor.**

Oerlikon Fairfield Planetary Gearbox

Oerlikon Fairfield has been making planetary gear drives under the Torque Hub name since the product line was purchased in 1972. Until the mid-1990s, most planetary gear drives with parking brakes used bolt-on brakes versus a fully integrated brake design. As gearboxes and hydraulic motors started to become more integrated into steering applications, the requirement for shorter gear packages became prevalent. Fairfield started integrating multi-disc spring-applied, hydraulically released parking brakes into the spindle of existing gearbox designs. This resulted in the main bearings being larger in diameter, permitting the length of the brake to be incorporated in the main bearings of the gearbox and thus shortening the overall length of the package. Today, this is still the primary means of integrating a parking brake into a planetary drive for hydraulic drives.

With the current trend of electrification of vehicles, the next iteration of gearbox designs has emerged. As the motors shift in applications from hydraulic to electric, the requirement for the brake has changed accordingly; the brake is now integrated closer to the motor, as opposed to the gearbox, meaning the hydraulic ports in the gearbox are no longer required. In addition, to reduce electric motor size and cost, the optimum planetary gearbox ratio has increased, making triple-planetaries a better option. In working with Ashwoods, Fairfield has taken a standard high-volume, double planetary gearbox with an integrated hydraulic brake and replaced the hydraulic brake with a small planetary inside the former brake cavity. Standard triple-planetaries in this product line add an additional 1.48" (37.6 mm) to the overall length. With this new design the extra length is not required while still allowing an overall ratio between 67.98:1 and 130.04:1. Figure 3 shows a section of the gearbox with the hydraulic motor attached. The area highlighted in red is the integrated hydraulic brake. Figure 4 shows the planetary gearbox with the Ashwoods IPM motor attached. The area highlighted in red is the third planetary stage.

The gearbox technology itself is a proven design in the industry; a radial lip seal is standard as are tapered roller bearings for the main bearings. A boot (V-ring) style seal is op-

Table 2 **Motor technology comparison**

Motor	Size	Weight	Peak Efficiency	Peak Power	S1 Power
Interior Permanent Magnet	207 × 99 mm	7kg	94%	9kW	7kW
Surface Mounted Permanent Magnet	273 × 125 mm	15kg	91%	10kW	3kW
Induction	170 × 225 mm	21kg	86%	10kW	3kW

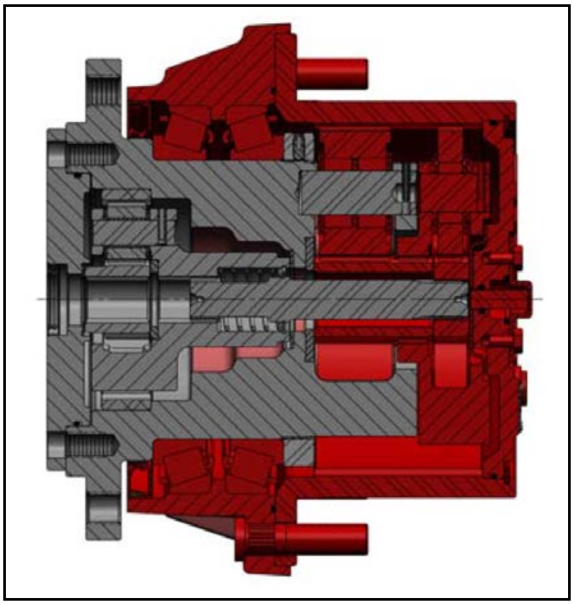

Figure 5 Rotating parts identified during mechanical disengagement of the drive (towing).

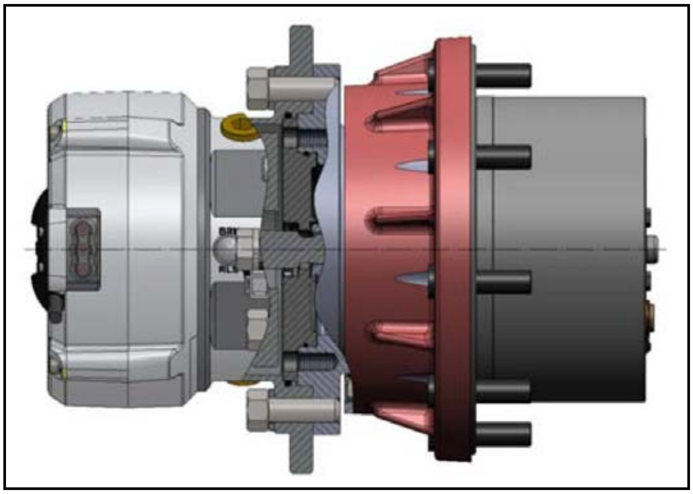

Figure 6 System integration.

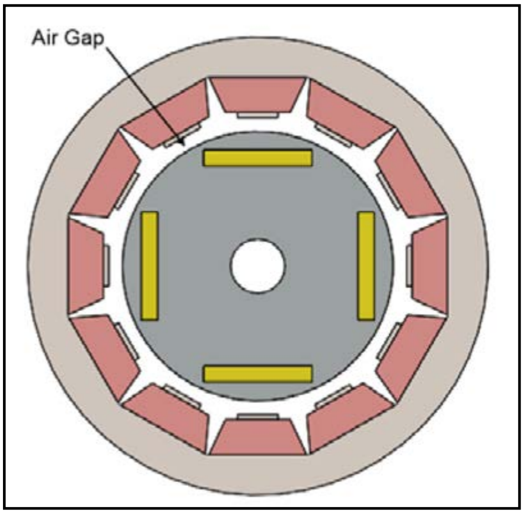

Figure 7 Mechanical air gap.

tional, depending on the environment the gearbox will be used in. An adapter plate on the spindle side of the motor will allow the gearbox to be adapted to the Ashwoods motor, while providing an additional radial lip seal to segregate gearbox oil from the electric motor.

Most Fairfield planetary drives also contain a manual disengage feature. This allows the end user to disengage the planetary from the motor so the machine can be towed. Normally, all three stages of the gearbox would be rotating under towing conditions, generating high turning losses and heat when pulled for extended periods. With the small planetary inside the spindle of this design, it is now engaged to the motor so only the last two stages will rotate under towing conditions, subsequently reducing gearbox drag, heat and noise. This also eliminates unloaded cycles on the high-speed planetary. Figure 5 shows the parts that will rotate highlighted in red.

Integration

The integration of the planetary and motor was accomplished through the use of mounting adapters. The first, mounted to the gearbox, is a modification of the adapter used on the standard Fairfield planetary, modified to accommodate a lip seal to isolate the electric motor from the gearbox oil. The second adapter mates the motor to the gearbox, which adapts the standard motor to the standard gearbox. Slight variations in this adapter would allow the motor/gearbox to be adapted to multiple frame and hole configurations. The adapter also serves as the mounting point for the electric brake. This allows the electrical components to remain together while allowing the mechanical connection between the gearbox and motor. It provides the primary bearing support for the motor shaft — the last component of the integration — as it serves as the shaft for the motor rotor, brake reaction and integration into the gearbox coupling.

The way in which the motor, brake and gearbox are integrated enables both the motor and brake to be contained within an IP65 enclosure. It also removes one of the bearings that would typically be required to support the motor and brake.

The Ashwoods IPM motor has been designed to enable it to be assembled as a ‘cartridge’. This means the working parts of the motor can easily be integrated into another component’s housing, such as an axle, pump or gearbox.

The mechanical air gap inside a radial flux motor is a factor that drives the way in which the motor can be integrated, and can complicate things such as housings and mechanical assembly. This is something that has been identified by Ashwoods and the solution offered means the motor can share a common housing and shaft without increasing the manufacturing complexity or cost. Figure 7 identifies the air gap within a radial flux motor.

Applications

Aerial work platform application. Up to now, current solutions used in production of aerial work platform machines (AWP) still utilize large, heavy and inefficient brushed DC or induction motors incorporated with planetary gearboxes. Some of the main issues for the machine manufacturers are limited vehicle range, limited space around the motor/drivetrain, and motor durability. Figure 8 shows a typical AWP platform layout using induction motors. Figure 9 shows the space saving that can be achieved using the Ashwoods IPM motor.

The solution presented by Ashwoods and Oerlikon will use a planetary drive (Torque Hub) with an integrated electric motor (IPM motor), while also housing a brake (parking brake/emergency brake) integrated into the complete package. This solution will open up packaging space on the vehicle while increasing vehicle range due to the efficiency performance of the motor.

Other Potential Applications

Despite the solution discussed in this paper being developed for aerial work platform applications, it is also suited to many alternative applications — some of which are outlined in this paper.

Mini excavator. Traditionally, mini excavators utilize diesel engines producing up to 50 kW of power. The engine powers the machine's hydraulics that provides the traction, cab rotation and digging functions of the machine. Due to increasing emissions legislation and the requirement for the machine to operate in zero-emission zones such as enclosed construction sites, factory spaces and built-up environments or indoor demolition applications, companies are looking at diesel–electric hybrid alternatives. This enables the manufacturer to downsize the diesel engine to power a generator while adding electric motors to operate the machine.

It has been identified that mini excavators with an engine power of 20 kW or similar will require around 7,000 Nm of traction torque at the tracks. This power and torque requirement fits inside the scope of the solution proposed by Ashwoods and Fairfield, enabling the hydraulic motors to be replaced with the Ashwoods IPM motor integrated to the Fairfield planetary gearbox. This solution will be IP65-rated, meaning it can be located inside the machine tracks and protected from contamination.

Forklift truck. Electric traction drives are already widely used in forklift trucks. A typical layout for this is shown (Fig. 10). A large majority of these applications utilize induction or brushed DC motors, thus limiting packaging space. Alternative solutions are also used, such as incorporating a common axle across the front of the truck. But this presents the same problem that limits packaging space. Further limitations are passed onto the packaging of the hydraulics, causing the need for longer hoses that ultimately have an effect on machine efficiency. The output characteristics of the solution proposed in this paper meet the requirements of many forklift applications. Figure 10 shows a forklift truck with two induction motors packaged into the front wheels. Figure 11 shows a concept using the solution discussed in this paper and the space saving that can be achieved.

Using this integrated solution will enable manufacturers to gain system efficiency — not only due to the motor technology used, but also due to improvements to the cable layout of the hydraulic system — improving the overall system efficiency.

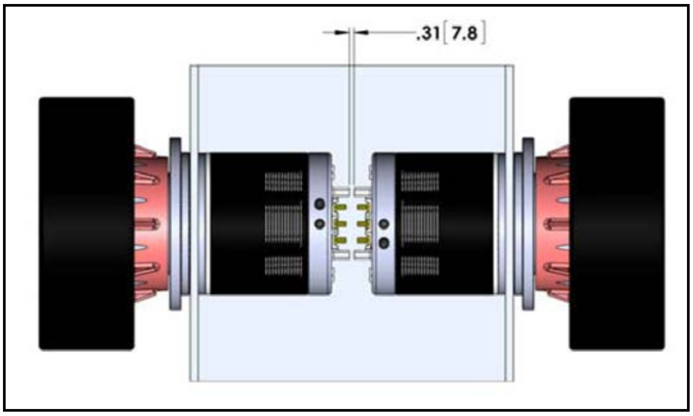

Figure 8 Induction motor packaging.

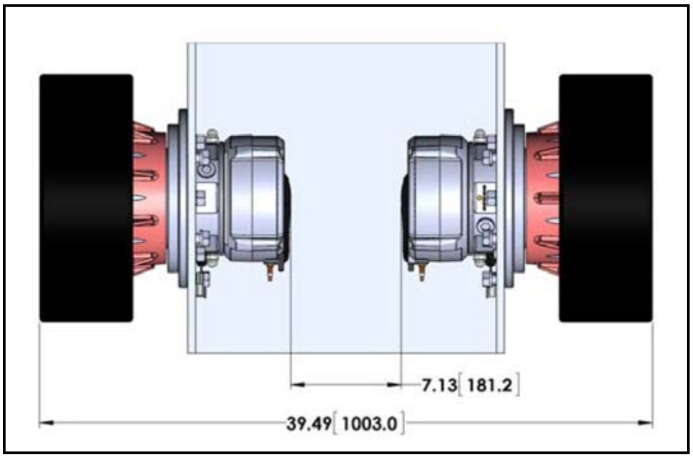

Figure 9 IPM motor packaging.

Figure 10 Forklift truck (http://skembedjis.com/product/clark-gex/, n.d.).

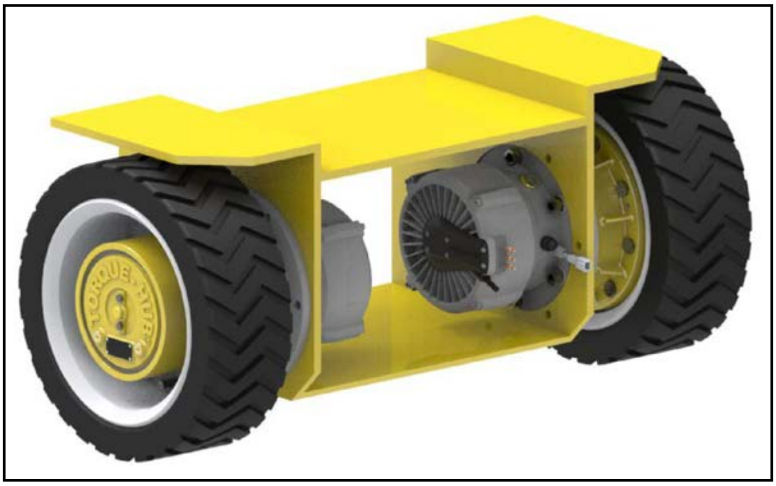

Figure 11 Concept forklift drive.

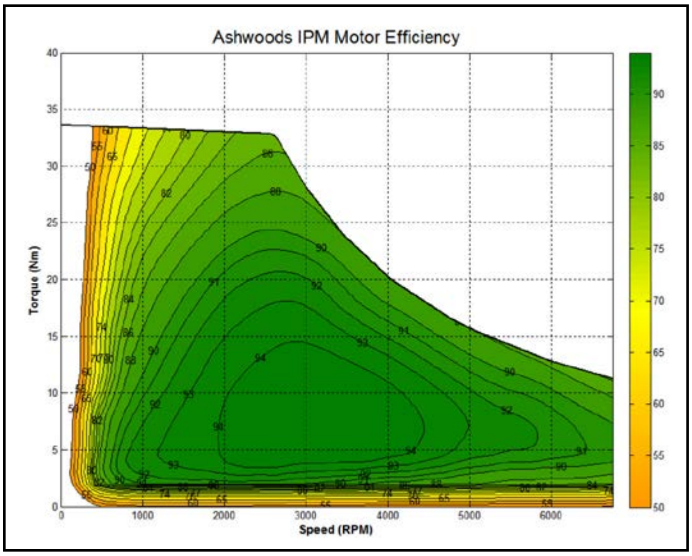

Figure 12 Efficiency map interior permanent magnet motor.

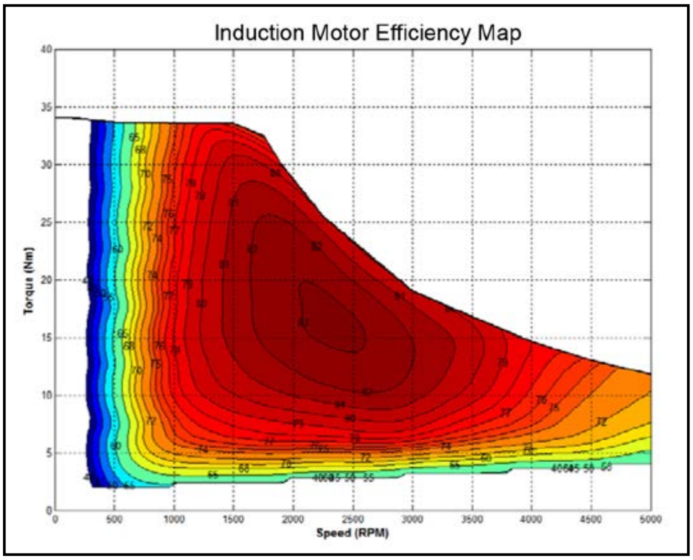

Figure 13 Efficiency map induction motor.

Further Applications

Other typical applications include, but are not limited to, commercial turf equipment, ground support equipment, light construction and industrial equipment. The benefits of using this integrated solution:

- Improved efficiency and performance without extra cost
- Extremely compact length
- Increased vehicle range with lighter vehicles
- Reducing customer application machine weight
- Easy and quick installation of the package
- Easy handling (in terms of cost and assembly on the vehicle itself)
- Bringing new innovation to replace old technology

A further benefit of using electric technology in applications that currently only utilize IC engines is related to testing and validation. Having the electronics associated with electric drives in a vehicle/application provides further options in regards to data validation. It also means fault reporting and diagnostics can be done remotely.

The motor and gearbox combination discussed in this paper is scalable and applicable to various applications. Both Ashwoods and Oerlikon Fairfield are working to extend the range of models available, some of which are identified in Table 3.

Table 3 Motor range

Motor	Frame Size	Voltage	Power	Gearbox
IPM-2-03-25	207 x 99mm	48-80V	9-12kW	7000 Series
IPM-2-06-12	207 x 140mm	48-80V	18-24kW	W6C
IPM-2-06-25	207 x 140mm	300-400V	25-37kW	18000 Series
IPM-3-03-25	260 x 99mm	600-700V	40-50kW	N/A

Testing and Validation

A major benefit of using IPM technology is the efficiency properties of the motor. Ashwoods has conducted extensive testing on their motors to optimize their efficiency properties. Figure 12 shows the efficiency map obtained from the motor identified in this paper. Comparison tests that have been done with a market-leading induction motor and the Ashwoods IPM design have shown a 20% increase in efficiency.

As stated, the thermal performance of an IPM motor can be a drawback due to its limited mass. For this reason Ashwoods has completed thermal testing on their IPM motors to represent different application drive cycles. The results shown in Table 4 are from a comparison test made with a best-in-class induction motor. The test represented a 3.5-hour transient cycle with dynamic loads showing a typical off-highway drive cycle for an application that would utilize the IPM motor. The results show the Ashwoods motor temperature initially rising at a greater rate than the induction motor, which can be attributed to the limited mass available on the IPM motor for heat distribution. But as the test continues the temperature

Table 4 Thermal performance

Motor	Start Temp (°C)	Temp after 10 mins (°C)	Temp after 30 mins (°C)	Temp after 60 mins (°C)	Temp after 200 mins (°C)
Ashwoods IPM	20	46	54	60	60
Induction	20	39	58	81	110

of the IPM motor equalizes and the induction motor temperature rises to 110° C without equalizing. This is largely due to the cooling design inside the IPM motor and its capability to reduce its temperature during the "off-load" periods of the duty cycle. Ashwoods plans to complete further testing with varying duty cycles to validate the IPM motors' thermal performance.

Further validation of the motor/brake/gearbox assembly has been completed at both Ashwoods and Oerlikon Fairfield. Two duty cycles have been applied to the assembly at Oerlikon to test the system's competency and durability. The first is a high-torque/high-speed duty cycle completed over 1,000 hours. The second duty cycle is low-speed and low-torque, but completed over 50,000 hours. The results from these tests have contributed to the system validation. Figure 14 shows one of the rigs used to carry out the durability testing. In addition to the validation work being conducted at Ashwoods and Oerlikon Fairfield, the motor/gearbox combination will be installed and tested in an application.

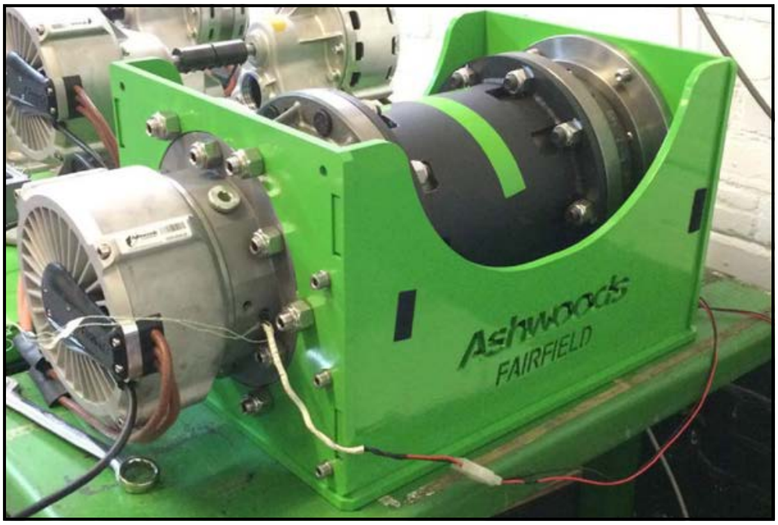

Figure 14 **Durability testing.**

A common failure mode for electric motors is an insulation breakdown in the windings due to over-voltage or fatigue. As mentioned in the (Interior Permanent Magnet Motor Technology section) the Ashwoods IPM motor incorporates encapsulated windings to reduce the risk of this failure occurring. To help validate the motor's durability, vibration testing has been conducted on the motor following IEC 60068-2-24.

Conclusion

The solution proposed by Oerlikon Fairfield and Ashwoods Electric Motors offers an alternative to the current electric traction solutions widely used in industrial and material handling vehicles. Advantages such space saving, efficiency increase, and reduced packaging constraints complement the solution.

Validation of the unit has been discussed and the concerns addressed. Application testing is now the next step for the unit and is scheduled to be completed in 2016. The performance of the proposed current motor frame size and gearbox has been discussed and potential applications for the solution, such as aerial work platforms and forklift trucks, have been identified. In conjunction with market research, the future models discussed will be developed and the associated applications targeted. **PTE**

References

1. *http://skembedjis.com/product/clark-gex/*. (n.d.). Retrieved from *skembedjis.com*.
2. *http://skembedjis.com/wp-content/uploads/2014/02/clark-forklifts-gex-drive-axle.jpg*.

James Winchester has since 2013 served as product manager at Ashwoods Electric Motors, responsible for co-ordinating development projects, identifying new market opportunities, forming strategic alliances and evaluating new technologies. Winchester holds a first class honors degree in motorsport engineering from Oxford Brookes University.

Andrea Favale is a product torque hub application and project engineer/off-highway for Oerlikon Graziano. He holds a degree in mechanics from Istituto Tecnico Industriale "A.Avogadro" located in Torino, Italy. He also received specialist training for CATIA 5 at Instituto Camerana Torino, specialist training for AutoCAD 14 at the Arte e Mestieri School and completed a basic course in German at the Academy International School. He began his professional career in 1998 as resident redactor of IVECO Torino, editing booklets for use and service maintenance for truck and bus vehicles. In 2000 he was employed in the R&D technical office of Technod s.r.l. as a designer for high-pressure fittings and manager of parts requirements for various customers. Since then he has served Oerlikon Graziano as R&D (designer) for bus axle/golf car application, including three months experience in the U.S. for training in planetary gears/gearboxes. In his current position Favale performance calculations relative to machine requirements for planetary drive products, including managing dedicated projects for tractor-type applications and technical support during the prototype phase; failure evaluation relative to planetary drives in the field; definition of the validation plan for the gearboxes in accordance with customer requirements; and managing repairs of broken gearboxes in the shop, ensuring delivery time and requested quality.

Scott Martin earned a B.S. in mechanical engineering technology at Purdue University in 1996. That same year he joined Fairfield Manufacturing/Oerlikon Fairfield as a project engineer. From 2000 to 2003 he served as a design engineer and from 2003 until 2012 as senior advanced product engineer. He also in 2012 worked as manager, drive products engineering, before assuming his current position.