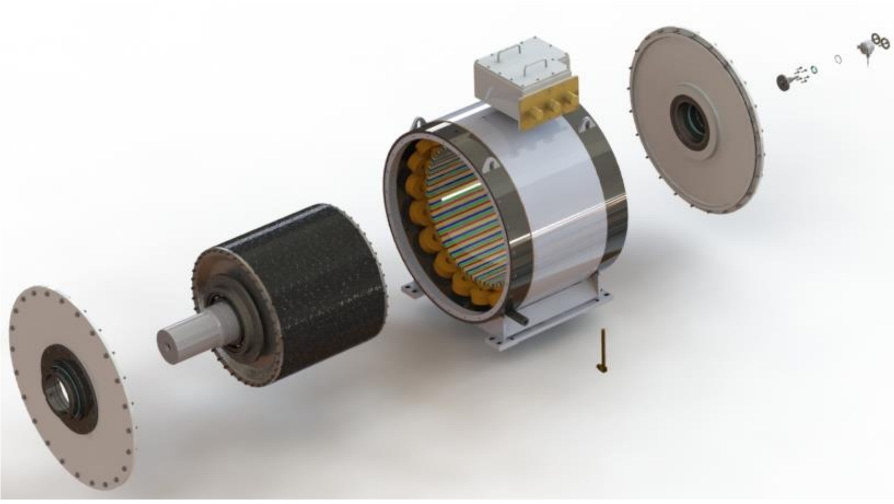
Project title: CAIMAN (IEEA 2016)



Summary

CAIMAN is aimed at improving drive train efficiency over conventional geared, belt driven systems for industrial shredder applications (Solid Recovered Fuel).

The CAIMAN Drive Motor (photo top left) has been designed by Magnomatics and constructed by ATB Group. It incorporates Magnomatics' patented magnetic gear technology and is known as a Pseudo Direct Drive (PDD®), combining a Permanent Magnet (PM) Motor with a Magnetic Gear to give unrivalled efficiency, compactness (torque density), reliability and a unique 'torque fuse' capability.

The Drive Motor was extensively Factory Acceptance Tested (FAT) on a bespoke dynamometer test bed at Magnomatics facility in Sheffield.

FAT testing was performed in place of site testing, following withdrawal of the industrial partner from the project and has successfully demonstrated the efficiency of the machine. Measured efficiency was very closely matched to the original predicted values so there is a strong case for follow on exploitation and to validate the predicted savings when installed in a suitable industrial application.

The Industrial Energy Efficiency Accelerator (IEEA)

The IEEA programme supports the development of innovative technologies that will help industry reduce energy consumption and cut carbon emissions. It focuses on innovations with large potential cross-sector energy and carbon reduction impact - either new technologies or established technologies applied to new sectors. Over £15 million in public and private funding has been committed to develop solutions through partnerships between technology developers and industrial companies willing to test technologies on-site. The programme is funded by the UK government (BEIS) and managed by the Carbon Trust, with support from Jacobs.

Introduction

The project was originally aimed at replacing the current Induction Motor, Reduction Gear and Belt Drive systems on a Solid Recovered Fuel (SRF) waste shredder, operated by Ellgia Waste Recycling, with a direct drive PDD Motor offering a 16% uplift in overall efficiency of the system (predicted). The project was allowed to continue under a similar scope, with support from BEIS, The Carbon Trust and Jacobs, to construct the motor and then test on a bespoke dynamometer to demonstrate the predicted efficiency and typical characteristics under representative conditions.

Using the high-efficiency PDD® motor, the project aimed to significantly improve industrial drive solutions by removing the lossy components such as gearboxes and belt drives common to existing technology. This was predicted to result in a simpler, higher reliability drive-train with approximately 16% savings in energy usage. It was expected that alongside reduced energy consumption, the new drive-train would also reduce maintenance schedules and increase reliability through negating components that are prone to wear. It would also reduce downtime due to blockages and subsequent mechanical gearbox and drive belt failure.

About the innovation

The PDD is a combination of a permanent magnet motor and a magnetic gear. The two parts of a PDD cannot be separated as the high-speed rotor magnets are part of both the motor and the magnetic gear. Therefore, it makes dual use of the high-speed rotor magnets. Figure 1 shows the permanent magnet motor components (stator and high-speed rotor) of a PDD. The fundamental flux from the high-speed rotor links the stator windings, resulting in a high-power factor (>0.9). Figure 2 shows the magnetic gear elements. The high-speed rotor magnetic flux is modulated by the pole-piece rotor to produce a dominant (higher order) harmonic in the outer airgap that rotates at a lower (geared) speed than the fundamental flux. The number of outer magnet poles is selected to be the same pole number as this lower speed harmonic, forming a synchronous geared coupling. As the outer magnets are stationary (connected to the stator), the rotating high-speed rotor causes the pole-piece rotor to rotate (this is the same as in a mechanical planetary gear where the planet carrier turns when the ring gear is fixed).

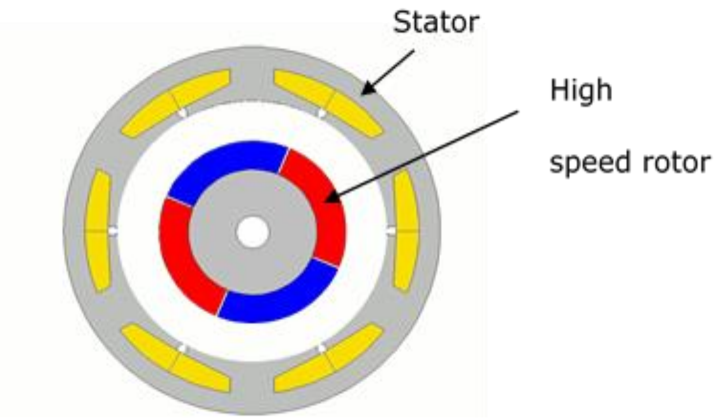


Fig. 1 PM motor

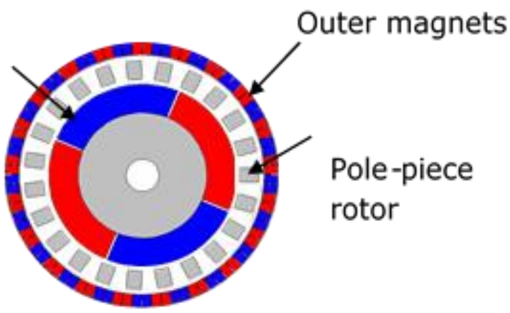


Fig 2 Magnetic gear

The PDD® motor overcomes the torque limitations of conventional direct drive electrical machines, without the disadvantage of mechanically geared systems, by integrating a non-contact passive magnetic gear within a permanent magnet brushless machine. This provides a speed-reducing, torque-increasing transmission which does not need lubrication. The high output torques on the input/output shaft are obtained utilizing the very high shear forces developed by the magnetic gear which is much greater than that of an electrical machine of a similar size. The electrical stator element is then smaller than other motors as it only needs to deliver a low torque due to the internal gearing (with gear ratios of 5:1 to 10:1 being typical). The windings operate with a low current density, leading to reduced copper losses and higher efficiency over the entire operating speed and load range when compared to permanent magnet brushless motors (current state-of-the-art). Figure 3 shows a cross-section of a typical PDD showing stator, output rotor (pole-piece rotor) and high-speed rotor.

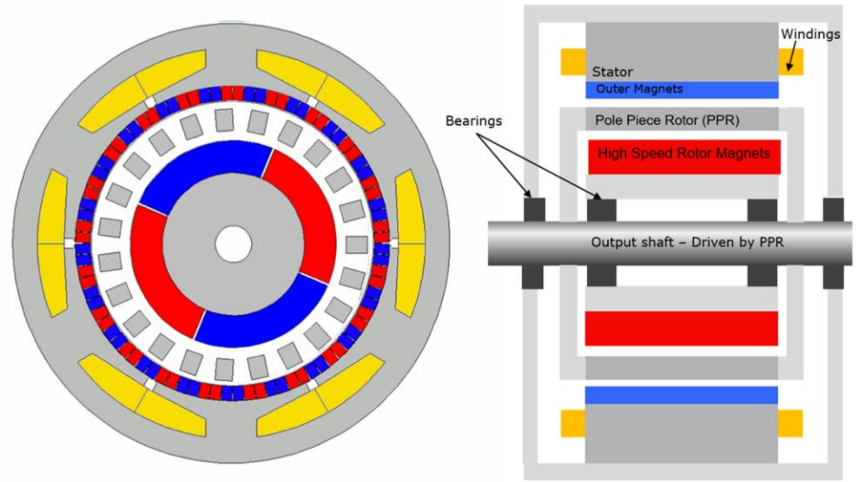


Fig 3. – Pseudo-Direct Drive (PDD) in cross section

In summary, a PDD can be thought of as consisting of two elements: a permanent magnet motor and a magnetic gear. The key benefits of this arrangement are:

- No mechanical gears but speed matching with the low-speed load is accomplished through the magnetic gear (typically between 5 and 10:1 ratio)
- Increased efficiency
- No transmission oil
- Low noise & vibration
- Torsionally compliant
- Improved reliability (Similar MTBF to an industrial motor – only bearings to maintain)
- Reduced maintenance
- Overload protection (this feature negates the need for a torque limiter)
- High power factor
- Very high continuous torque density (ideal for most industrial applications)

The above features are beneficial to industrial motors, with some providing a level of functionality that is not possible in existing motors. For instance, the overload protection afforded by the magnetic gear provides a "torque fuse" type function that negates the need for a mechanical torque limiter that is usually present in a shredder application for the occasions where hard, solid objects are injested into the rotor blades. Ordinarily, this would cause the torque limiter to be activated which requires resetting and downtime. The torque limiter itself is also a high cost item and needs replacing regularly.

The PDD provides a passive means of limiting the torque. When the load torque on the magnetic gear rises above the maximum designed transmission torque, the device harmlessly slips, and the average output torque drops to zero. This protects the drivetrain components. Once the fault is cleared, or at least the torque levels return to levels that are within the operating range of the gear, it passively re-engages. This feature is particularly useful for shredding applications and for many crusher or stirrer applications where occasional high loads due to the material types being processed can cause drive-train failures. Magnomatics have successfully run magnetic gears in this “pole-slip” state for over 100 hours with no detriment to the motor due to the non-contact transmission, offering a highly reliable and low maintenance means of delivering power.

Figure 4 shows an airgap shear stress comparison of various magnetic devices that transmit torque, either passively through permanent magnets (couplings and gears) or via electromagnetic means (PM motor and PDD). It can be seen that the PDD requires significantly lower current density. Airgap shear stress is a common method of comparing electrical machine technologies by calculating the force per unit area acting at the airgap radius which is between the stator and rotor. The higher the shear stress (measured in N/m2 or Pa) the higher performance the machine in terms of torque density. For a PDD, a typical shear stress for a continuous rating is >120kPa whereas a PM motor is often less than 60kPa. The PDD is limited by the magnetic gear maximum transmissible torque, but it can maintain this on a continuous basis thanks to the internal gear ratio. PM motors cannot provide this level of torque density on a continuous basis as shown in Figure 4.

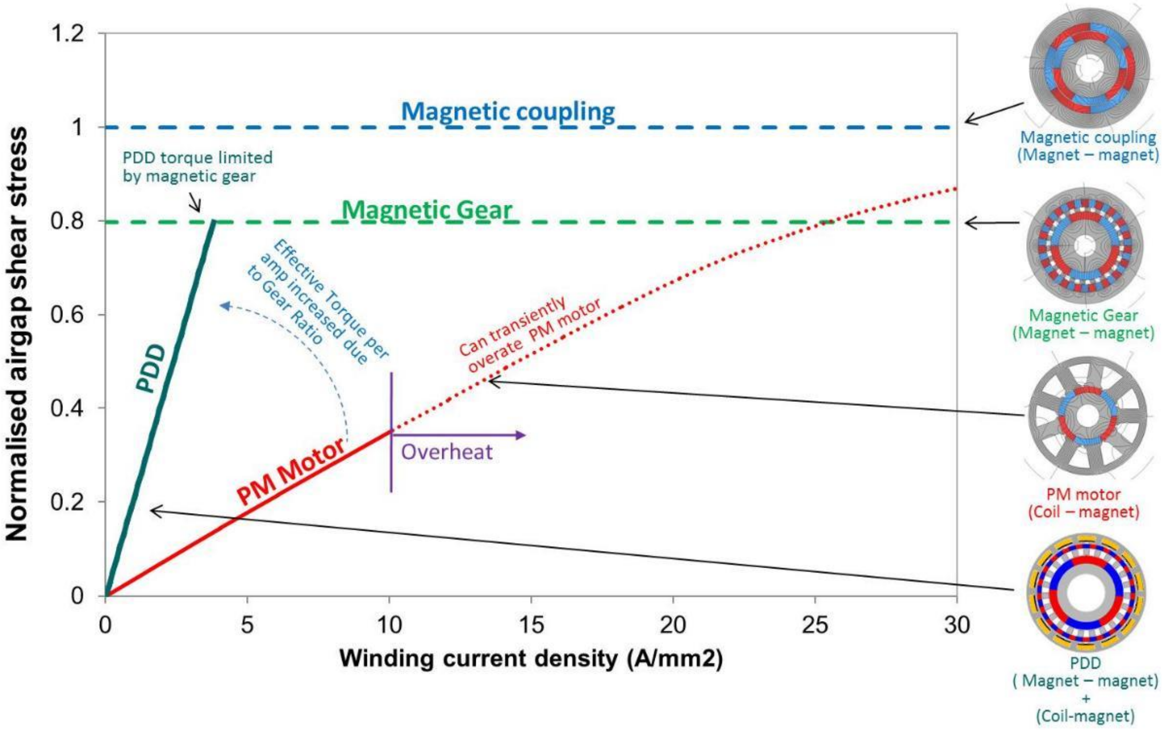


Fig 4. Comparison of electromagnetic rotating machines in terms of normalised airgap shear stress

The demonstration

Magnomatics have many years of experience and expertise with dynamometer testing at their dedicated facility in Sheffield. Their team comprises mechanical and electrical engineers as well as specialised test engineers and the latest measurement and data acquisition systems to measure and verify machine characteristics.

CAIMAN was installed on a bespoke test bed incorporating a load motor, drive shafts and gearbox and a high accuracy torque transducer to measure input torque to the motor (see Figure 5). Dedicated variable speed drives provided the power to the load motor and the CAIMAN motor. Figure 6 shows a photograph of the dynamometer during testing at Magnomatics' facility in Sheffield.

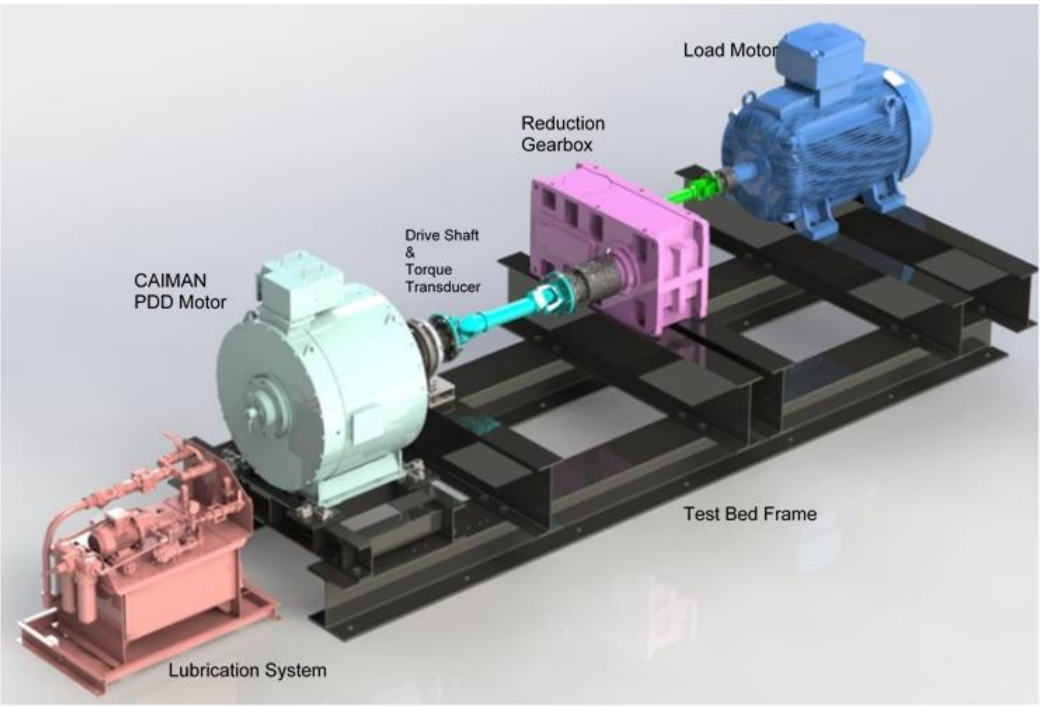


Fig 5. Diagram of test dynamometer set-up at Magnomatics

Fig 6. Photo of the dynamometer test-rig at Magnomatics facility in Sheffield during testing

Test Results

CAIMAN was tested through an extended, comprehensive Factory Acceptance Test (FAT) at Magnomatics in Sheffield. This was conducted in place of the industrial site testing planned at Ellgia after they pulled out of the project. Table 1 shows the extended FAT test plan.

Table 1 – FAT test performed

		Parameters	Criteria	Purpose	Notes
PDD **Oil lubricated and water cooled**	**No-load parameters**	Back EMF constant measurement	Within 5% of predicted Voltage versus rpm. Verify frequency of waveform	Terminal voltage as a function of speed.	168 V Phase RMS @ 180rpm PPR speed @ 20degC HSR PM
		No-load drag loss measurement	No load drag loss at a range of values up to 180rpm PPR.	To determine the baseline electromagnetic and mechanical losses prior to on load testing.	Consider seal / bearing losses
	On-load performance	Torque constant measurement	Torque per amp within 5% of predicted value at base speed. Verify phase current as predicted at 5000Nm	Establishes ratio of electrical machine torque over rms phase current. Also checks for linearity.	Kt = 25.2Nm/Arms [17,302Nm, 687Arms @ 80°C] Limited to 12,500Nm due to max current availability from Emerson Drive. Limited by acceptable temperature and/or by max current available from the Emerson Drive (100°C on winding / 80°C outer PM)
		Efficiency measurement	Efficiency map over torque-speed range.	Pass/fail determined by value at rated torque and speed. Does not include inverter losses	Subject to maximum operating point. Limited by acceptable temperature and/or by max current available from the Emerson Drive (100°C on winding / 80°C outer PM)
		Over-speed test	Machine over-speed to 120% at no load. Machine must operate at full spec post-test without damage (re-test & visual inspection)	Maximum speed is overload speed. Record any issues during run up.	Rated speed = 180rpm Over-speed = 120% Over-speed = 180 x 1.2 = 216rpm

The results of the extended FAT tests are shown in Table 2.

Table 2 – Table of Results

Test Title	Condition	Result
Back-EMF	No-Load	**PASS** 160V RMS @180rpm (within 5% of predicted)
Drag Loss	No-Load	Drag loss was found to be 47% higher than predicted. This was attributed to additional electromagnetic losses due to poor construction of the stator, and additional oil churning losses (from lubrication oil) not considered in the original calculations. This equates to a 1.3% reduction in efficiency at rated operating point.
Torque per Amp	On-Load	Between 25.2Nm/A and 25.7Nm/A @40°C (estimated HSR magnet temperature). Results are within 2% of predicted.
Efficiency Map	On-Load	**95.5%** @rated operating point. Based on this result, the whole drive system is predicted to be 14.6% more efficient than incumbent technology for SRF production.
Overspeed	On-Load	Not conducted – overall test plan truncated following magnet retaining feature failure
Pull-out test	On-load	Not conducted – existing dynamometer drive used for FAT testing was current limited

Magnomatics have investigated the additional drag losses since the tests were carried out. The losses are assumed to be due to two main factors:

1) Poor manufacturing of the stator magnet retaining features causing short circuits between individual laminations and also between the laminations and stator magnets, causing eddy currents to flow locally.

2) Lamination burrs and coating removal due to LASER cutting (mainly on the small retaining features as they were more prone to rapid heating during cutting) causing the same effect (higher eddy current losses).

Magnomatics have already developed a technique to reduce the losses due to both of these effects and will be demonstrating it on a larger machine in 2022. The originally predicted efficiency of 97% should be achievable with the simple changes implemented.

Future impact

The extended Factory Acceptance Testing performed on the PDD Drive Motor has validated the predicted savings very successfully with observed efficiency of the Motor around 95.5%, close to the 97% originally predicted. If there is a future opportunity to incorporate the PDD Motor in a shredder at a later date the impact set out below could be validated.

Current system efficiency (315kW shredder):

Power cable 99%; IE3 motor 95%; 3 stage reduction gearbox 89%; Drive pulley mechanical efficiency 95%, Inverter 97%. From 315kW input power, 237.3kW of motive power is therefore transferred to the shredder with an overall system efficiency of 77%.

Magnetically geared (PDD) system efficiency (315 kW SRF Shredder):

Power cable 99%; PDD efficiency 95.5% (measured at FAT); Inverter 97%. The total efficiency of the PDD drive system is 92% which represents a 14.6% power saving (46kW per unit).

This 14.6% uplift in efficiency would result in predicted savings of 200,539 kWh/year for the 315kW SRF Shredder alone, with savings for the entire site (total of three shredders) around 601,619kWh/year if the site were on grid electricity.

In terms of market potential. the total SRF and RDF produced in the UK is around 16 million tonnes per year[1]. A typical 300kW shredder will produce around 8 tonnes of SRF per hour so 16 million tonnes are produced in 2 million operating hours. The values in the table below assume the UK SRF market is growing at 10%/year. The total sector savings after 5 years could be 146GWh.

The efficiency measured during FAT testing has been used to re-calculate sector-wide energy savings for a 2021 grid (industrial) conversion factor and results are shown in Table 3. The total energy savings and tonnes of CO_2 equivalent savings over 5 years, assuming 10% market growth and increasing penetration rates indicated in column 2 of Table 3, are 146GWh and 39,702 TCO_2e, respectively.

Table 3. Energy savings based on 2021 grid conversion factors (industrial) adjusted to reflect measured efficiency

Updated based on measured PDD efficiency results			
Year	Penetration rate	Energy saving (GWh)	Tonnes CO_2e
1	5%	4.60	1251
2	10%	10.59	2879
3	20%	24.35	6624
4	30%	42.01	11427
5	40%	64.41	17520

Conversion factor taken from: *[conversion-factors-2021-full-set-advanced-users.xls*] – available online from DEFRA.

The efficiency benefits will manifest as much higher returns in CO_2e savings from sites that still use Diesel generators to power the shredders due to the relatively poor Diesel conversion factors.

[1] Tolvik 2016 briefing report - UK export market.

Innovation lessons

The CAIMAN project has allowed the partners to develop a cutting-edge novel magnetically geared motor that offers many advantages over incumbent technology in terms of efficiency, maintenance and overload protection. It improves upon existing solutions by removing the lossy components (induction machine, gearbox and belt drive), resulting in a simpler, higher reliability drive-train with ~15% savings in energy usage. It is expected that alongside reduced energy consumption, the new drive-train could reduce maintenance schedules and increase reliability through negating components that are prone to wear. It would also reduce down-time due to blockages and subsequent mechanical gearbox equipment failure.

Magnomatics have learned a significant amount from the project in terms of advancing their technology, in particular, the potential for improving design to increase robustness and reliability. The project suffered manufacturing challenges for the stator that were not foreseen. Stator lamination production (cutting of electrical steel sheets) was originally planned to be carried out at ATB Group on their Weingarten press (rotary punching machine). However – it became clear after many trials that completing the job on this machine would be extremely challenging. We took the decision to move the work to Coleherne to finish the laminations with a LASER cutter. Once the laminations were built up into a stack to form the stator, it was apparent that the laminations had some registration problems for the slots where the magnets were due to be inserted which ultimately caused problems installing the magnets (some of the slots were extremely tight). This caused high loads on some of the retaining features for the magnets (some of these were manufactured from glass fibre) and it was noted on first commissioning tests that we had a noise issue on rotation of the machine. The machine was sent back to ATB Group for investigation, disassembled and checked, and nothing found so the machine was returned to Magnomatics. Commissioning continued at Magnomatics, and early testing started. The abnormal noise (and this time increased no-load loss) prompted Magnomatics to disassemble the machine on-site and it was found that a few magnets had become detached due to failure of the retaining system, causing damage to the rotor too. Magnomatics removed these magnets and replaced them fibre-glass fillers to get up and running as soon as possible and re-wrapped the rotor with composite fibre. Most of the tests were completed with this repaired stator and rotor, but testing was ultimately brought to an end by recurrence of the magnet retaining feature failure.

Magnomatics have already redesigned the stator to accept another retaining system – this time all steel – which has worked effectively in our larger machine. Magnomatics intend to produce another stator outside of the project and retrofit it in the CAIMAN motor to demonstrate the high reliability and robustness of this different system.

There was also an issue with the drag loss being higher than predicted. Magnomatics have deduced that this is probably to do with eddy currents flowing between the magnet retaining fingers axially due to poor insulation. This has been traced back to production methods where it was found that LASER cutting has caused the insulating coating to be removed locally. In combination with the burrs caused by the LASER cutter, this results in a conduction path axially, and thus higher eddy current losses than predicted. Magnomatics have already adapted the design of the stator to use a different coating material and method of post-processing the LASER cut laminations to remove burrs. Electrical conductivity tests showed much lower conduction with these stacks.

ATB Group have enhanced their learning and skills relating to manufacturing permanent magnet electrical machines and machines with novel technology that is challenging in terms of manufacture, tooling and assembly as well as skill sets for manufacturing personnel.

A key barrier to overcome is to persuade potential industrial partners to adopt new technology where the initial costs and risks may be higher than incumbent technology. CAIMAN was intended to be site tested but the restructure of the project due to COVID-19 changed this plan to one of extended FAT testing. The results from FAT testing are very positive and will be used to leverage interest in many industrial markets going forwards. The realisation of a fully built and tested industrial demonstrator motor should hopefully attract more interest than would be the case for a paper study and CAD model.

Contact information

Andy Knights-Cooper- Senior Project Manager

+44 (0) 114 241 2570

a.knights-cooper@magnomatics.com

www.magnomatics.com

Industrial Energy Efficiency Accelerator delivered and supported by:

Department for Business, Energy & Industrial Strategy

CARBON TRUST

Jacobs

Disclaimer

BEIS, the Carbon Trust, and Jacobs give no warranty and make no representation as to the accuracy of this report and accept no liability for any errors or omissions.

August 2022