

Electrifying the powertrain business

The rush to electric power is now in full swing, with automakers scrambling to bring battery models to market. But while much attention is being lavished on improving battery technology, Ricardo engineers are achieving significant efficiency gains through an integrated approach to electric powertrain design. **Jesse Crosse** reports on developments that will extend EV range – and even help reduce battery costs

Electric vehicles have arrived in a big way: big-name launches are a regular occurrence and almost every automaker has one or more plug-in models in its forward product programme. In short, EVs have moved into the mainstream.

For the motor industry, this means a major move away from traditional methods of design and manufacture, and the new challenge of embracing the potential that an all-electric powertrain offers. New battery electric vehicles (BEVs) provide the opportunity for a fresh approach to design and manufacture – witness the VW Group's much-promoted MEB modular EV component strategy.

Yet, despite VW's best efforts, sales of electric powertrain components by established EV manufacturers and suppliers to third parties have so far failed to take off in anywhere near the numbers needed to accelerate overall EV production. This could indicate the need for a more holistic approach to EV powertrain design, rather than the current practice of specifying a series of individual components. Accordingly, Ricardo has been thoroughly investigating many different EV powertrain configurations – and the work has led to the design of an innovative 'three-in-one', multi-speed

Electric Drive Unit (EDU) concept.

"Efficiency is clearly important," explains Rob Parkinson, Ricardo's global technical expert for transmission and driveline systems. "However, cost is paramount if EVs are to be adopted in larger numbers, and it's fair to say that nobody in the industry is absolutely clear as to which kinds of technology collections are going to be most cost effective overall. That's fundamental to the work we're doing now with EDUs."

Key to developing these new EDU concepts is a Ricardo-developed toolchain consisting of a variety of Ricardo and third-party software packages, all linked together to create a Design of Experiments optimization process capturing electrical, mechanical and thermal energy flows. Interrogating the results from the toolchain gives clear recommendations as to which powertrain and combination of sub-system technologies is best suited to a given vehicle.

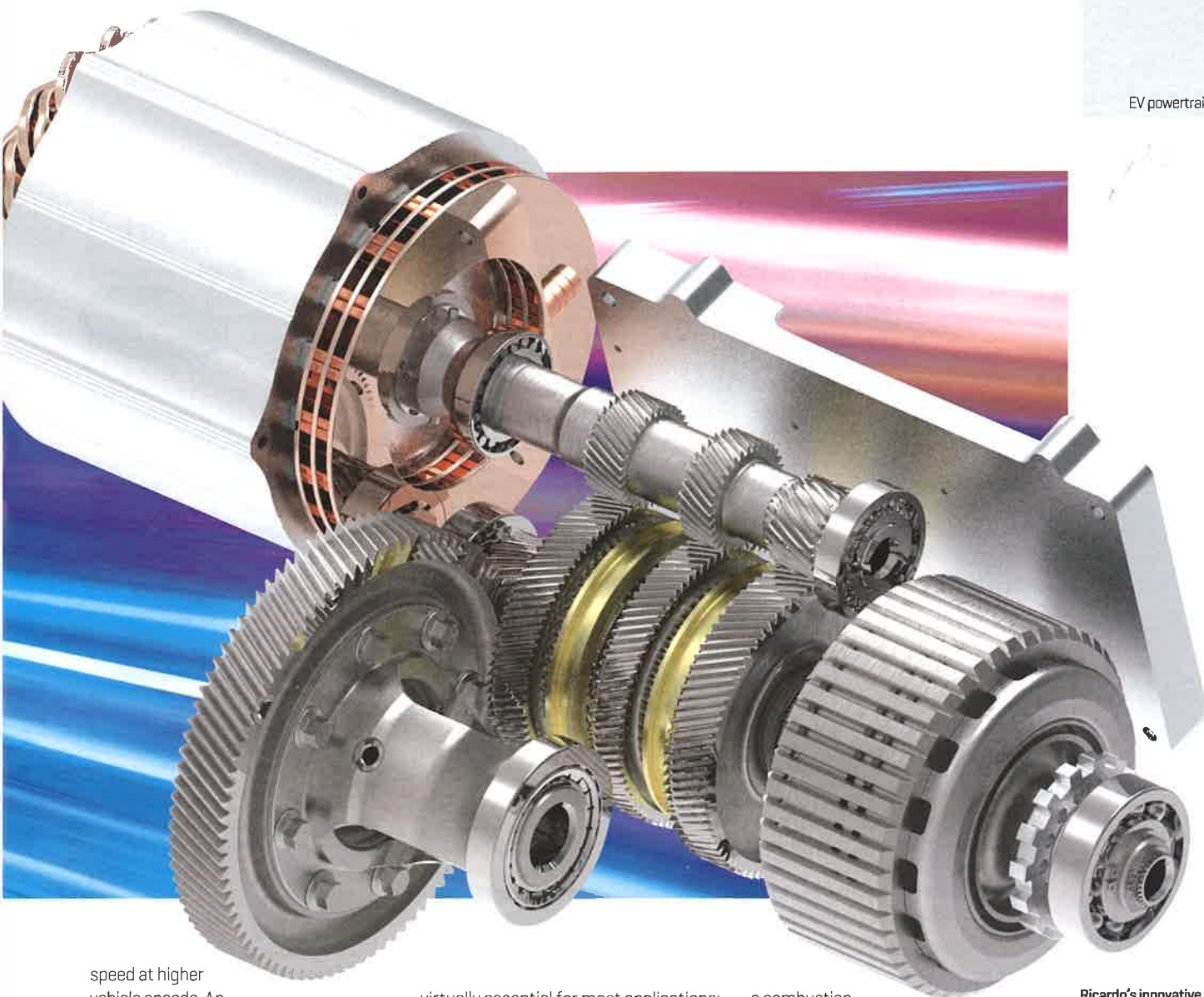
System approach makes

Combining an EV's electric motor with the transmission and power electronics to make a single unit is an effective way to improve efficiency and reduce cost. Scalable technology of this type could

be used by EV manufacturers across a range of EV classes – and an optimum solution that has emerged from Ricardo's work is a multi-speed EDU incorporating a three-speed dual clutch transmission, electric machine (motor), final drive and inverter.

Traditional practice has been for the transmission, electric machine and inverter to be developed separately and assembled together, simply because each component has represented a separate, expert discipline. "The downside of that approach," explains Parkinson, "is ending up with separate parts that are not necessarily perfectly attuned with one another, whereas designing an integrated system delivers the optimum combination."

Why opt for a multi-speed rather than single-speed transmission? At first glance a single ratio would seem a less complex and cheaper option. The answer lies in requirements of the electric machine used to power EVs. In a single-speed solution, the electric machine has to provide both peak torque at low speeds and peak power at higher speeds, through a single gear ratio. In the multi-speed option, explains Parkinson, "a lower ratio delivers more torque at the axle and a higher ratio reduces the electric machine



speed at higher vehicle speeds. An electric machine of a given power can be smaller in terms of torque output as well as dimensions and weight."

There are also efficiency benefits to be gained by using more than one transmission gear ratio. A traditional combustion powertrain has brake specific fuel consumption sweet spots or 'BSFC islands' in its operating range. "They are quite narrow and constrained within the working range of the engine," Parkinson continues, "but with several gear ratios you can use islands in multiple locations throughout the vehicle speed range. With an electric machine, the efficiency island extends much further over the speed range than a combustion engine, but there are still areas where it's less efficient. Using more than one ratio solves the problem, and we've seen efficiency gains of 4 to 5 percent."

Multi-speed technology does not suit every application, however, and for low-speed, lightweight city cars with small batteries, says Parkinson, "frankly, you can forget it. A multi-speed won't give you a benefit, but for a car with a wider working speed range and a bigger battery then, yes, it does." For the largest vehicles like trucks, it is

virtually essential for most applications: "Rather than attempting to make a big truck motor capable of both getting up a hill and cruising at speed on the straight and level, the solution could be to use a smaller motor with a multi-speed transmission."

Faster is more efficient

Ricardo senior global technologist Professor Andrew Atkins sheds more light on the benefits of using high-speed motors: "Going to higher speed reduces the electrical losses by delivering power through speed rather than torque. Torque and rotor volume are linked, so by reducing the need for high torque the rotor volume can be reduced as well. Moving to higher speed solutions and multi-speed transmissions sits well with forthcoming 800-volt technology because high-speed motors need higher voltages."

A more subtle aspect of smaller, high-speed electric motors which is less marked in low-speed motors is the 'torque ripple' effect. This phenomenon is due to the fact that electric motors have preferred positions during each rotation: at speed, these manifest as non-linear torque rippling. While far less marked than the torque spikes which occur in

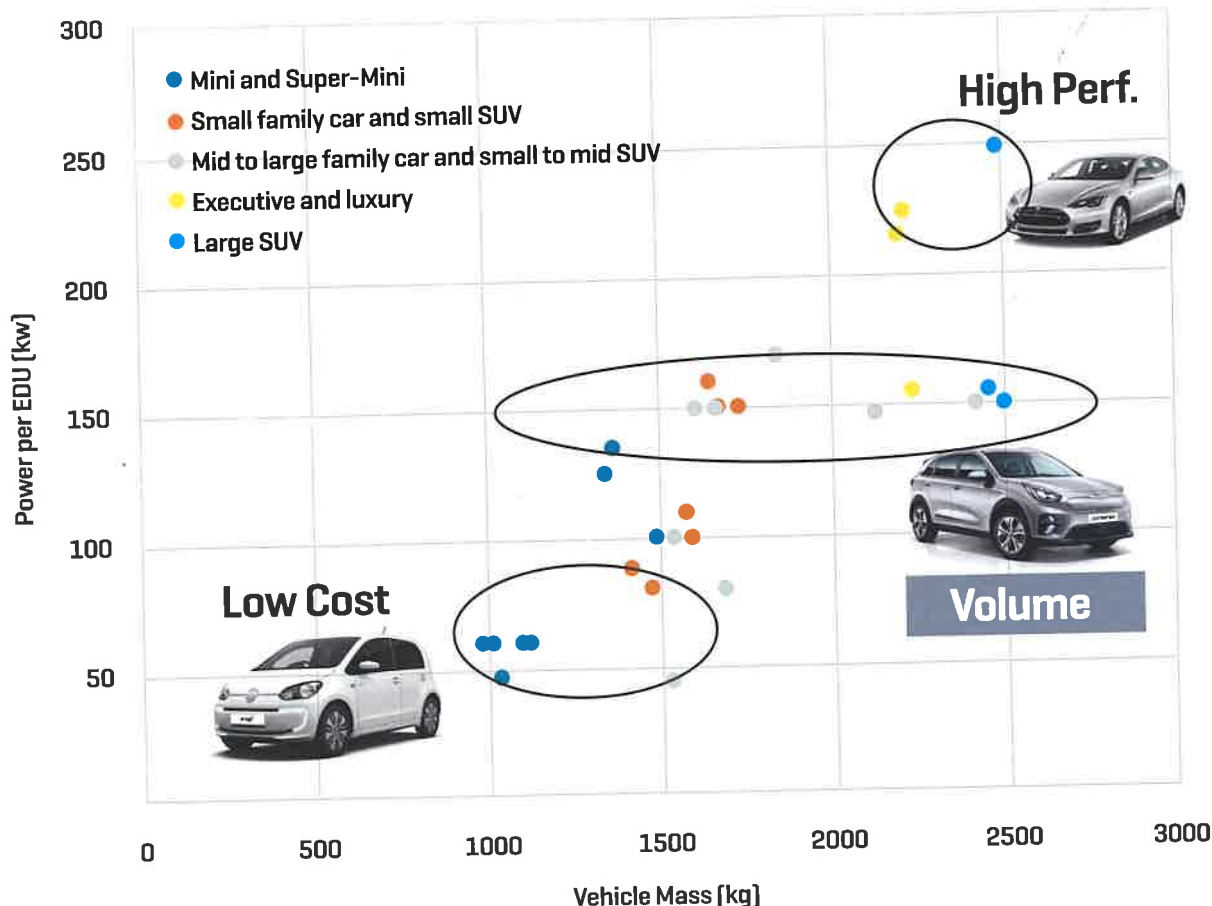
a combustion engine every time a combustion event occurs, it is still significant.

As electric machine speed increases, the amount of permanent magnet flux across the air gap creates more torque ripple and this can lead to gear rattle in the transmission, as well as other NVH [noise, vibration, harshness] issues. "With a combustion engine giving a significant torque fluctuation you can use dampers to iron that out before it gets to the transmission - but with electric machines you don't attach any kind of mitigation device and they drive the transmission directly," explains Parkinson.

However, torque ripple can be controlled electronically. "Looking at electric machines in other applications, servo motors are used in high precision manufacturing and can be minutely controlled. Automotive permanent magnet machines are fundamentally the same technology," says Atkins. "Using the power electronics, we can almost make them play a tune. With our transmissions team and motor controls team working together we can push the boundaries further forward. It may turn out that something we previously used the motor control algorithm for can be done better

Ricardo's innovative three-in-one Electric Drive Unit (EDU) concept. This can be adapted to deliver the optimum cost-performance-efficiency trade-off for different market sectors and product types

Ricardo predicts a wide range of electric powertrain requirements across vehicle sectors, but typically falling into three categories. Each of these can be served by an adaptation of the Ricardo EDU concept



→ with a transmission control algorithm, and vice versa. This is why the integrated approach is so important."

With speed comes efficiency

A further benefit of high-speed motors is that, generally speaking, they are intrinsically more efficient. Low-speed high-torque motors require higher

current, generating more heat – and this equates to wasted energy. "This is why I keep coming back to the fact that we need higher voltage to go faster. You don't get something for nothing," says Atkins.

Novel transmission concept

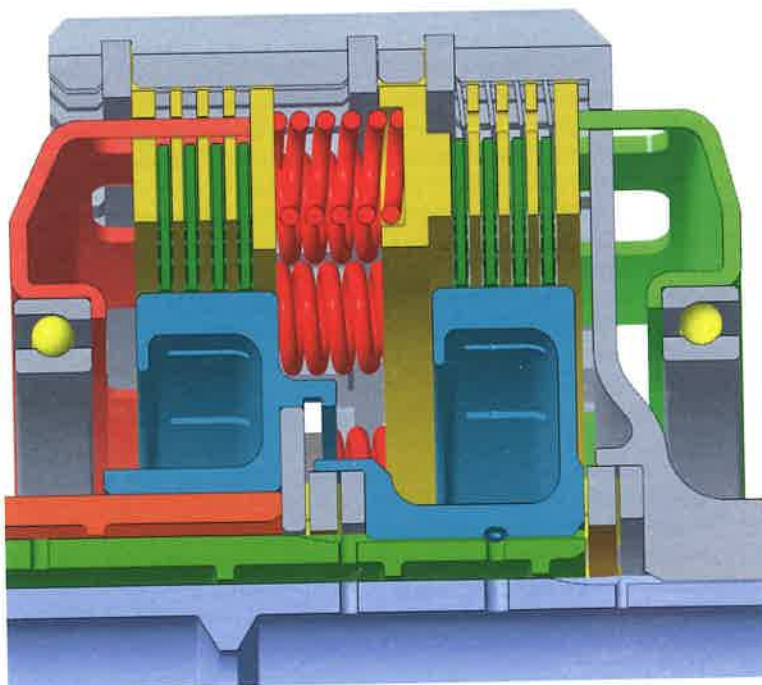
The transmission of the new EDU concept is a three-speed, wet dual clutch

unit, configured around a mid-sized, two-wheel drive SUV. "I don't think it will ever be necessary to use more than four speeds whatever the application," says transmission specialist Rob Parkinson. "The number of speeds chosen for a given application depends on several factors, such as efficiency, cost, packaging, inverter, motor and other vehicle attributes. In most applications the decision will be driven by the cost versus efficiency balance – for example, the fact that cost can be taken out of the battery by increasing range through driveline efficiency."

Wet clutches protect against wear, providing longevity and raising the potential torque threshold of the transmission across a wider range of applications. The design is unusual because the default position for the clutches is one closed and one open: the usual practice in most cases is for both clutches to be open. In the EDU the closed clutch is attached to gears one and three and the open clutch to gear two, the logic being that no energy is required for closing the clutch on gears one and three, only two. There's a good reason for this; under the WLTC cycle 70 percent of the driving time is spent in first or third gears. Synchronizers are included on all three ratios so idle gears are disengaged to avoid losses in the clutch.

Key features of the 3-speed DCT solution

The clutch pack has been designed with a focus on minimising losses, to improve overall vehicle driveline efficiency. The dual clutch is normally closed on 1st - 3rd intermediate shaft to maximize efficiency (over 70 percent of time is spent in 1st or 3rd gear over the WLTC). Opposed actuation limits loads on shaft bearings and leads to smaller bearings and less frictional losses. A synchroniser on 2nd gear in addition to 1st and 3rd gears further reduces losses



Oil cooling makes sense

Even with so much optimization, a multi-speed system still incurs additional losses compared to a single speed because of its additional bearings and clutches, its gear train and its pump requirements. "The raw output from our toolchain simulations helped us arrive at the best approach to take to minimize those ancillary losses," says Parkinson.

The oil cooling of the EDU is a good example: a single cooling system draws heat from the transmission, electric machine and inverter. If the oil is routed in series rather than in parallel it is possible to reduce the flow rate and minimize energy consumption. Cold oil flows first to the inverter, then the electric machine and finally the bearings in the transmission. Starting from cold, the system picks up heat through losses in the motor and inverter which then helps heat the transmission oil, reducing friction in what is a neat, virtuous spiral.

The entire system is sealed for life, but that is not without its challenges. "There's some work still to do with transmission oil being used in three-in-one EDUs," thinks Parkinson. When using a transmission oil to cool all three elements, the fluid collects magnetic debris from the wear in the gearbox

parts and it's not clear at this stage what impact that could have on the electric machine over time. Also, the specific heat capacity of oil is much lower than that of water, so for the same energy flow more coolant flow is required. Despite that, says Parkinson, "we've made real improvements in the extraction of heat using our oil-filled cooling system. One big advantage of cooling electric machines with oil is that the fluid is not conductive and so lends itself to a closer level of cooling inside the machine than water."

- The cost, packaging and weight saving of bringing all the parts together in one unit is already a huge benefit. Add to that the further benefits of a combined cooling system using just one pump rather than two or more, as well as using waste heat from one element to warm up another, and the unit becomes a fully optimized system.

On the electrical side, internal connections using bus bars instead of external cabling save cost and weight and improve safety. Reducing cost through efficient design is crucial. Economies of scale can be harder to achieve than with conventional vehicles because the cost of raw materials – such as copper and rare earth magnets – is so high.

Power electronics, however, are an area where high production numbers can really make a difference, says Atkins. "About 30 percent of an inverter cost is in power switches, and as we start to see a significant volume of these components, the overall cost of them will come down."

New players for a sustainable future

Beyond the EDU projects, how does Atkins see electric machine technology progressing generally?

A relatively new player in the field is the axial flux electric machine. In contrast to the cylindrical profile of a radial flux machine, the axial machine is more disc like. "These machines are axially very short and there are some applications where, for packaging reasons, they are more suited than radial flux," he says. Axial flux machines are good at producing high torque at low speeds, but for high speeds the radial flux machines come to the fore.

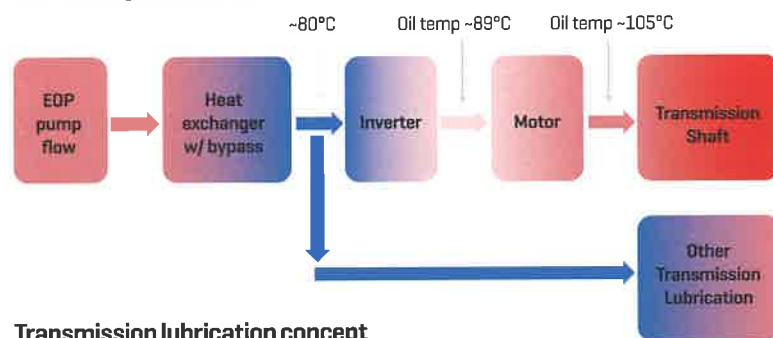
Prompted by sustainability concerns around rare earth materials, an emerging trend is a move away from permanent magnets. Conventional machines are classed as interior permanent magnet, but there's a move towards increasing reluctance torque in production EVs. "These machines still have permanent magnets in them but they are moving more towards synchronous reluctance operation to reduce the amount of rare earth material needed," Atkins continues. "The machine can be run at faster speeds and cost and weight are reduced."

The likelihood of synchronous reluctance electric machines becoming more common is enhanced by the use of multi-speed transmissions because there is less reliance on torque. Unlike switched reluctance or full permanent magnet machines, the technology does not produce very high torque at low

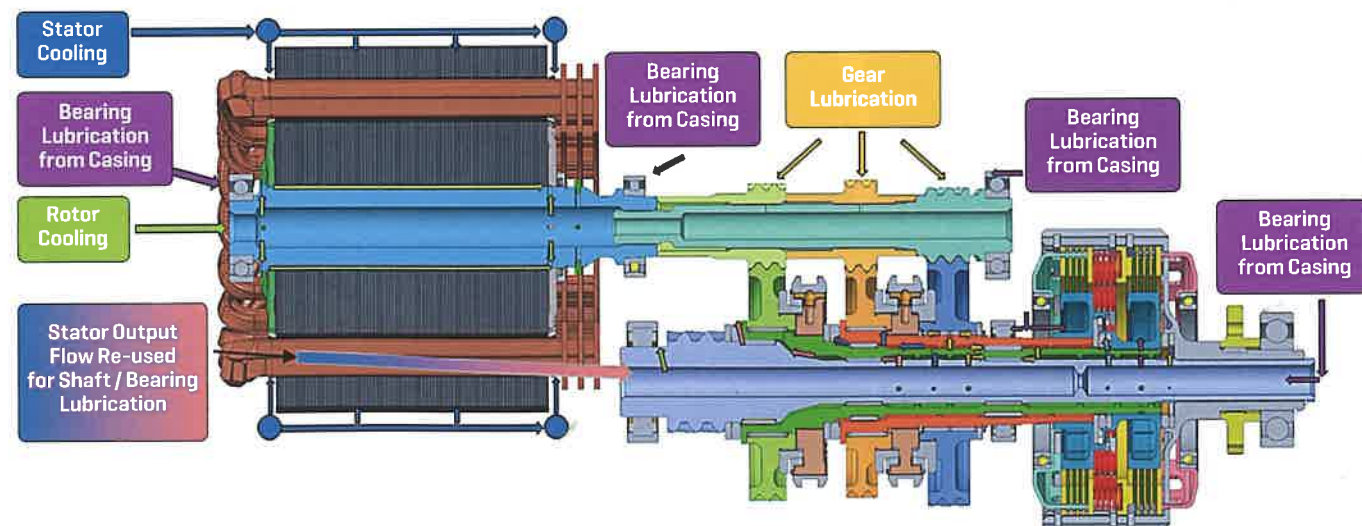
EDU cooling circuit design

Oil flow from the heat exchanger provides the lowest temperature oil to the inverter for improved inverter thermal stability. Inverter flow output is then supplied to the motor cooling in series to reduce electric oil pump flow requirements. Collection and re-use of motor stator output flow into transmission shaft bearing lubrication allows for further EOP flow reduction whilst also assisting with transmission warm up

EDU cooling and lubrication flow overview

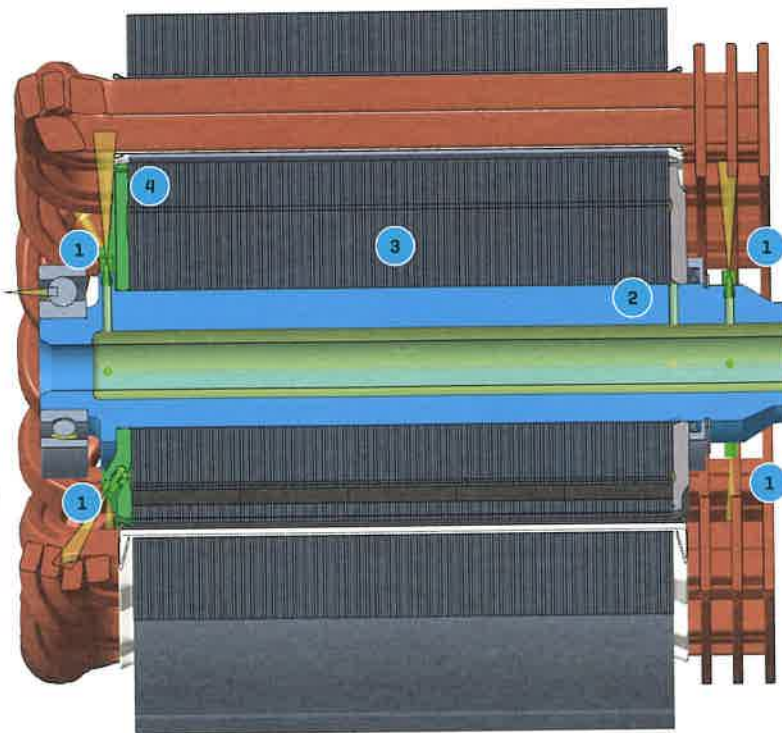


Transmission lubrication concept



Motor cooling

The EDU motor is cooled using the transmission oil, using ten jets on each side to cool the end-windings (1). No cooling of the back-iron needed thanks to active jet end-windings solution efficiency. The magnets in the rotor are also oil cooled as follows: holes feed the oil from the shaft into the void behind the end cap (2); the inner flux barrier beside the magnets is used as an oil gallery (3); the oil feeds out through jets in the end cap at the free end (4)



speeds. Applications like excavators, which need very high torque at minimum speed, would require switched reluctance solutions instead, but for passenger cars, synchronous reluctance motors in conjunction with multi-speed transmissions would be ideal. "This would take us further down the path of eliminating the use of rare earth metals altogether," Atkins continues. "There's a real possibility of replacing the

permanent magnet with ferrite solutions too." Work is also going on to replace copper windings with aluminium, which is cheaper, lighter and more abundant, but has a higher resistance than copper and more of it is needed in the windings.

Formula E racing and the future

Ricardo has three years' experience working with DS Performance in

Formula E. The DS Automobiles Techeetah racing team won both the manufacturers' and drivers' championships in the 2018-2019 season. "In a Formula E grid, 80 percent of each car is the same," explains Ricardo business development manager for Performance Products, James Sundler. "Only the electric machine, inverter and gearbox - designed by Ricardo - is different."

Using software it had developed in house, Ricardo was able to predict the overall efficiency of the driveline, minimizing oil churn, seal drag, bearing drag and so on, to develop the most efficient transmission possible. The software is so accurate that it is possible to predict differences as small as 0.5 percent - and because there is a direct correlation between overall driveline efficiency and lap time, any reduction of losses in the driveline improves the performance of the car. The very important lessons learned in this demanding field are expected to cross over into road car development.

What comes next? Ricardo is continuing its research into producing high efficiency cost-effective electric powertrains capable of underpinning not just BEVs but fuel cell electric vehicles as well. What is clear from the work so far is that treating an Electric Drive Unit as a single system rather than a collection of separate components gives significant efficiency gains - and the best thing is that there is still more to come. 

