Compact In-wheel Motor for Passenger Cars and Light Commercial Vehicles

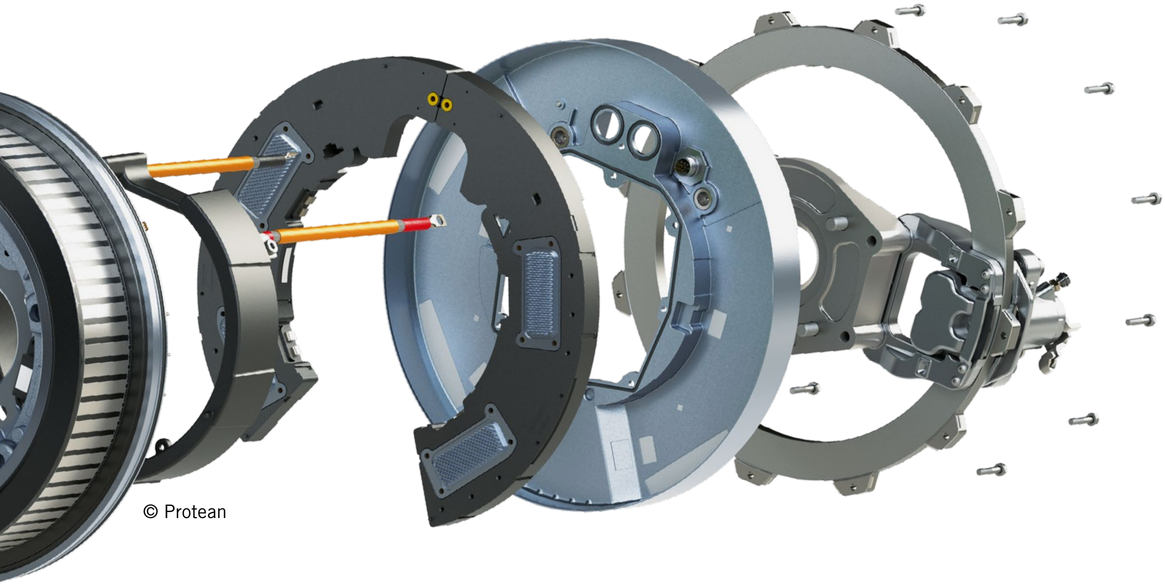
Protean Drive is an in-wheel electric motor system for passenger cars and light commercial vehicles. The motors occupy the space inside the wheel rim and incorporate a mechanical brake, which traditionally occupies this volume.

Vehicles may be configured in two- or four-wheel-drive configurations, as either fully electric or hybrid, and with 400 or 800 V battery systems. A pair of in-wheel motors represents an alternative to a more conventional electric axle, in which a motor and inverter are mounted on the vehicle body and drive is transferred to the wheels through a gear, differential and half-shafts. An illustration of a system using four in-wheel motors is shown in **FIGURE 1**.

The in-wheel motors are direct drive, meaning there is no gearbox or transmission. The electric machine is a Permanent Magnet Synchronous Motor (PMSM) with an outer rotor. The inverter is integrated within the same package as the motor. The integration of all the components inside the wheel provides a major space saving compared to a conventional electric axle.

BENEFITS OF IN-WHEEL MOTORS

The space saving from using in-wheel motors creates an opportunity for re-packaging the electrical components. For example, a common drawback for electric vehicles is the position of the battery. In most electric cars, the battery is placed in the floor in a so-called skateboard design, **FIGURE 2**. The effect of this packaging is to raise the floor by approximately 150 mm. This forces the vehicle designer to either reduce cabin space for the occupants or to raise the height of the roof, causing an increase in air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Protean Electric has developed an in-wheel drive system that integrates motor, power electronics, digital controls and friction brakes in a compact housing. Protean Drive offers a higher degree of design freedom for manufacturers and can even be used to convert existing vehicles to hybrid or fully electric vehicles.

WRITTEN BY

Richard Burke
is UK Engineering Director
at Protean Electric
in Farnham (UK).

FIGURE 1 Example of a vehicle platform powered by in-wheel motors (© Protean)

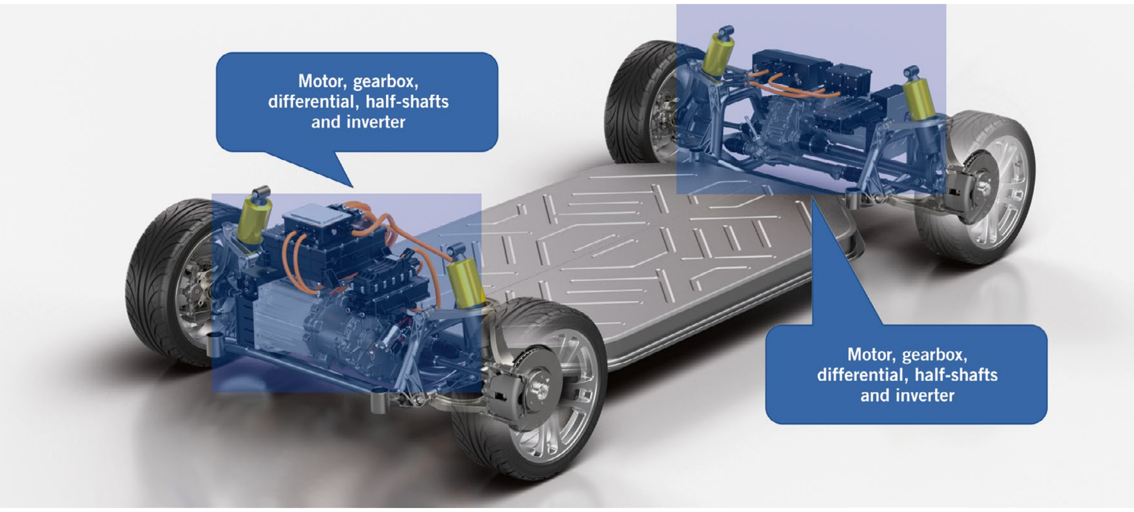


FIGURE 2 Illustration of a vehicle platform using conventional electric axle (© Protean)

resistance and a corresponding reduction in range.

An alternative battery packaging concept using in-wheel motors is shown in **FIGURE 3**. In this example, batteries are packaged to leave space for the passenger footwells. This arrangement of battery cells provides the same charge capacity as a skateboard battery but enables the vehicle designer to increase the cabin space for occupants without raising the height of the roof.

Batteries also benefit from a reduction in the mass of the drivetrain components for a vehicle using in-wheel motors compared to an electric axle. Deleting mass allows the option to either reduce the battery capacity or increase the range from an existing battery.

A further benefit of in-wheel motors is the torque vectoring capability of such a system. Torque vectoring is the application of differential torque across an axle and is a zero-cost feature of in-wheel motor systems, achieved by demanding different torque outputs from left and right motors. This allows understeer and oversteer characteristics to be optimized dynamically. Torque vectoring can also reduce turning circle radius in rear-wheel drive applications, allowing the rear wheels to work with the turned front wheels. By applying torque vectoring to the rear axle of a car, the turning circle may be reduced by between 7 and 10 % without making vehicle changes, **FIGURE 4**.

In conventional vehicles the suspension system is compromised to achieve the desired understeer and oversteer characteristics and steering self-righting behavior. Since these features can be achieved using torque vectoring, the suspension system can be optimized for ride quality without compromising vehicle handling.

CHALLENGES FOR IN-WHEEL MOTORS

Despite the benefits offered by in-wheel motors, their design introduces several challenges. One of the major difficulties faced by the engineers was packaging the motor and inverter into the space available inside a wheel rim. The goal was to minimize disruption to other systems at the wheel-end, such as the wheel bearing, suspension, steering and friction brake. The large diameter annular volume lends itself to a high radius, axially short, high torque motor, but the volume is not ideal for packaging an inverter. Protean Drive is designed such that standard wheel rims, bearings, suspension and steering systems may be used, but the brake disc has to be inverted compared to conventional solutions. A typical integration with suspension and brake is shown in **FIGURE 5**.

The environment in which the in-wheel motor operates necessitates a design that can withstand vibration and shock. Vibration testing is carried out over 32 h in each of the three axes at an average of 11 *g* rms acceleration in accordance with the GMW3172 standard [1]. In addition, the design must handle 20 shock accelerations of 100 *g* in both directions in each axis.

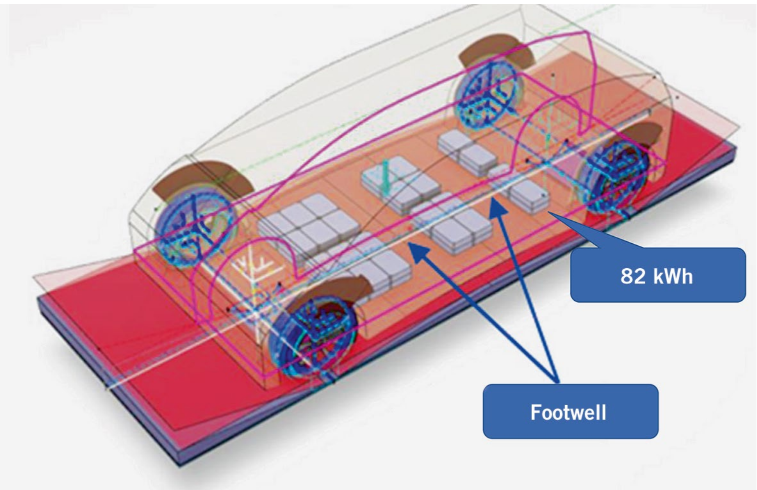


FIGURE 3 Battery packaging concept using in-wheel motors (© Protean)

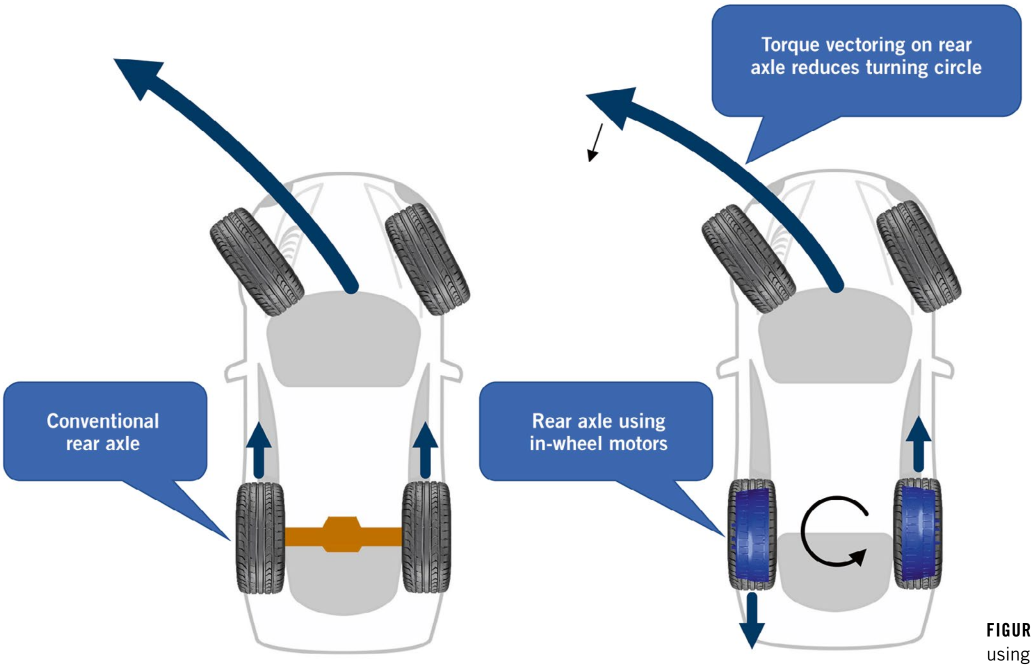


FIGURE 4 Reduction in turning circle using in-wheel motors (© Protean)

Sealing is also more of a challenge compared to a motor and inverter in a conventional electric vehicle. The system may need to stand in water and is subjected to dust, grit and other materials during its lifetime. The function of the dynamic seal is further complicated by the deflection of the wheel-bearing during cornering and heavy braking, which in turn means that the seal must tolerate relative movement between the rotor and stator.

Heat must be managed in the system. The motors are cooled with a 50:50 water-glycol-mix that can typically remove around 5 kW of heat at the nominal flow rate of 13 l/min. The motor windings, inverter and friction brake are all sources of heat. Typically, windings can withstand up to 180 °C, electronic components up to 125 °C and capacitor elements up to 100 °C. During operation, the brake disc may reach temperatures as high as 500 °C; The disc is connected to the rotor, meaning that heat conduction to the drive magnets must also be taken into account.

Noise, Vibration and Harshness (NVH) is an important consideration for in-wheel motors. The large diameter external rotor is a potential source of noise if the excitation of the magnets by the electromagnetic field is not carefully constrained by design. This is further complicated by the non-linear characteristics of the electric motor, which are largely a consequence of the compact design. The ability to tailor the phase current waveforms by inserting harmonics of the fundamental electrical frequency at the right amplitude and phase can reduce torque ripple such that the level of structure-borne noise in the vehicle cabin is acceptable for high quality passenger cars.

No discussion about the challenges of in-wheel motors would be complete without a mention of unsprung mass. It is indisputable that in-wheel motors add mass to the unsprung parts of the vehicle. What is less clear are the effects of that increase. Conventional wisdom is that any addition of unsprung mass is problematic and should be avoided at all costs. The reality is more complex. From a theoretical perspective, for example [2], the critical factor is less about

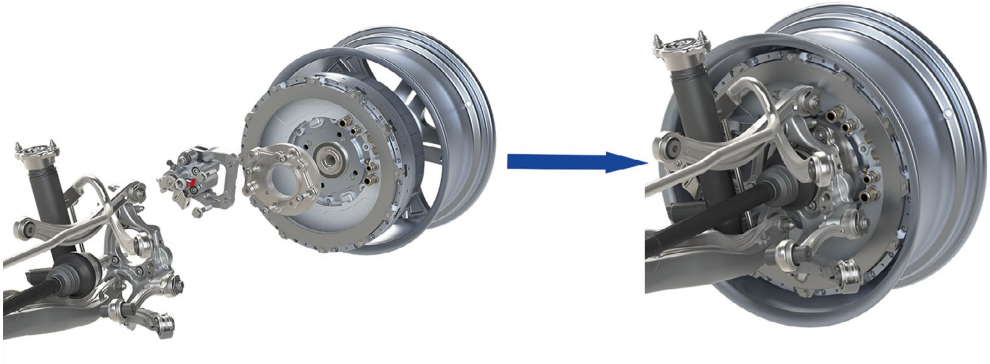


FIGURE 5 Protean Drive integration with suspension and brake (© Protean)

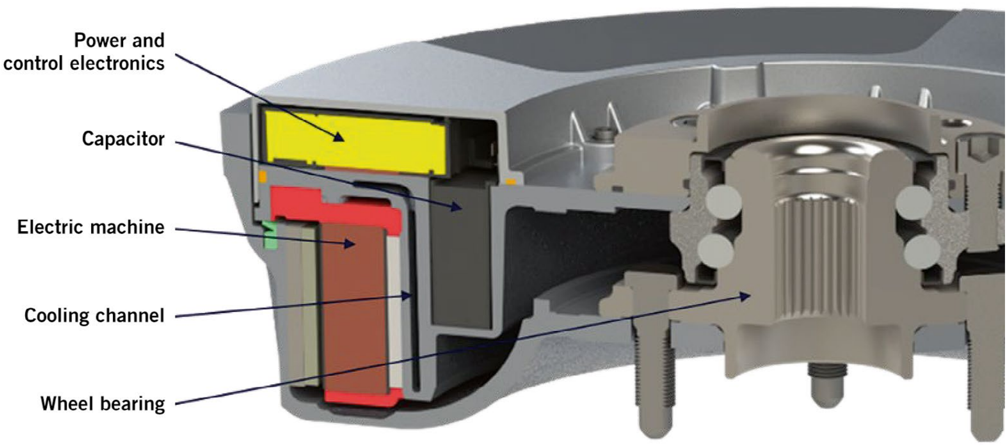


FIGURE 6 Arrangement of electronics, capacitor and electric machine in the stator (© Protean)

the absolute unsprung mass and more about the ratio of sprung to unsprung mass. This coincides with findings that the effects on handling when installing in-wheel motors are barely noticeable by all but the most experienced drivers in larger vehicles and are more than compensated by the benefits of fast torque response and torque vectoring. On the practical side, Protean has commissioned several studies on the effects of unsprung mass, including an evaluation by Lotus Engineering [3]. This paper concluded that while the differences in performance are measurable using sophisticated engineering techniques, none of the differences are beyond normal deviations from target in a typical vehicle development programme.

MOTOR CONSTRUCTION

The design was dictated by the space available to package the electric machine and the inverter. The volume available is annular. The wheel rim constrains the outer diameter, the wheel-bearing limits the inner diameter, and the total axial length is constrained by the wheel rim width and the requirement to incorporate a friction brake. For example, a Protean Drive motor-inverter designed to fit in passenger cars with 18-inch wheel rims and to deliver 1400 Nm torque output has an outer diameter of approximately 400 mm, an inner diameter of 200 mm and a total axial length of about 140 mm.

The power and control electronics associated with the inverter are distributed on the vehicle (or inboard) side of the package. The capacitor is a custom-designed part that occupies a ring on the inside of the electric machine. The main body of the stator is a machined aluminum casting that acts as a heat-sink; cooling channels run on two faces of the electric machine and also cool the power electronics.

The power electronics design uses 650 V rated Insulated Gate Bipolar Transistors (IGBTs) in a custom module. Each power module consists of a three-phase inverter, and each unit incorporates four of these modules. The arrangement of coils and inverters is shown in **FIGURE 6**.

The stator comprises an aluminum body, manufactured from a casting, onto which a back-iron is fitted in a hot-drop process. The back-iron is formed from a stack of laminations of electrical steel,

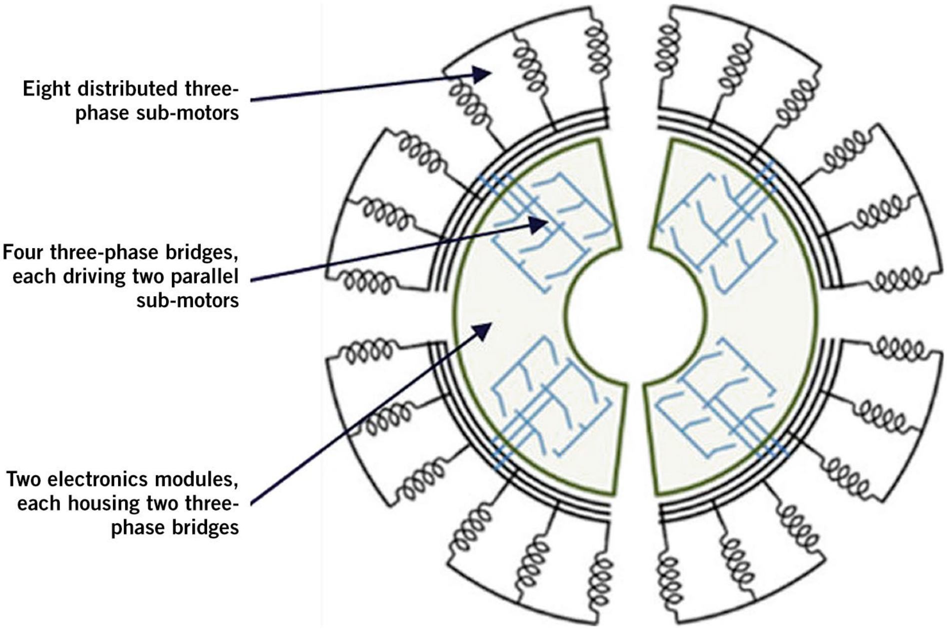


FIGURE 7 Schematic representation of the drive architecture (© Protean)

and the dimensions are selected such that at all operating temperatures, there is an interference fit between the two parts, capable of handling the maximum torque.

The electromagnetic design of the stator consists of plug-in teeth that are pressed into the stator back-iron. In total, there are 72 teeth, each wound with 32 turns of copper wire. During manufacture, an automated winding machine wraps the wire around three consecutive teeth to make up a phase. The phases are linked together via leadframes to configure the electric machine as eight 3-phase sub-motors, with two sub-motors wound in parallel, **FIGURE 7**.

The stator body is water-cooled. The coolant channel is configured as two layers; the first layer provides cooling to the power electronics and the second to the coils and stator back-iron. The system uses a 50:50 water-glycol mix at a nominal flow rate of 13 l/min. The cooling channel design is shown in **FIGURE 8**.

A pair of power electronic modules are mounted to the back of the stator, each housing two three-phase bridges. The rear of the stator is protected from the environment via an electronics cover.

The rotor is manufactured from an aluminum casting. During manufacture, the rotor housing is heated, and a back-iron is inserted. The dimensions of the two parts are carefully chosen to ensure there is an interference fit between them at all vehicle operating temperatures.

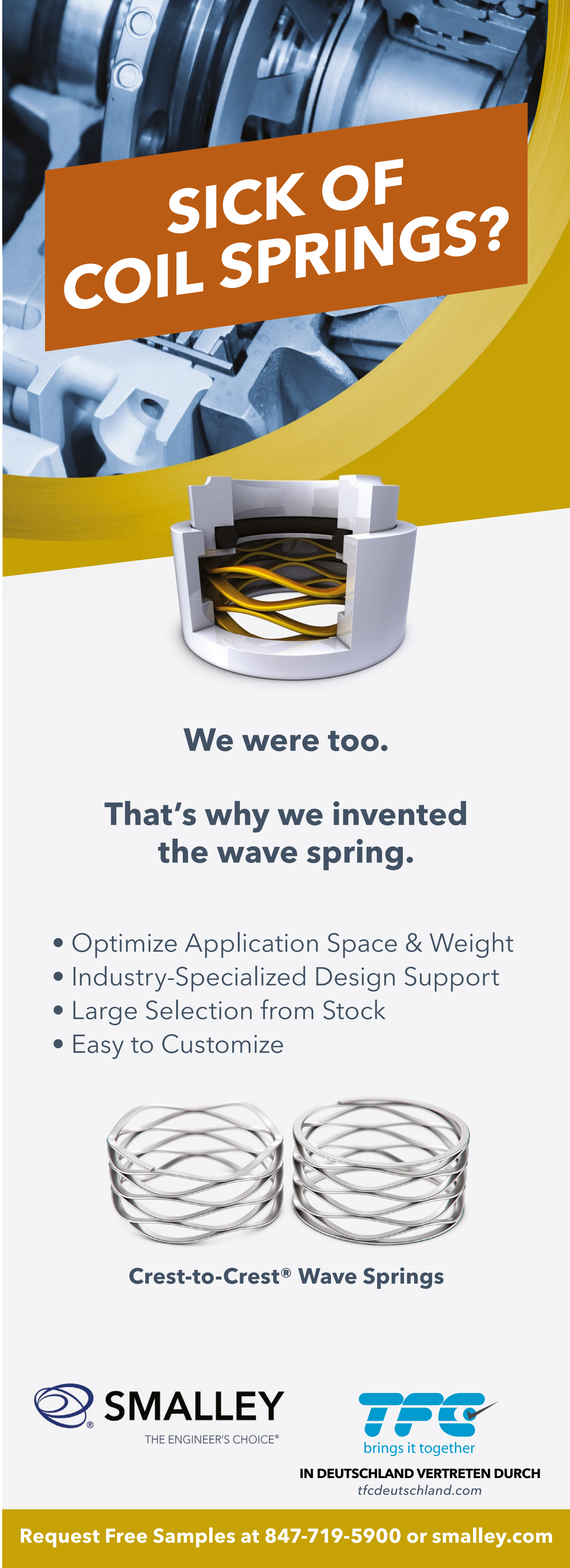
Thirty-two pairs of drive magnet stacks are bonded to the interior surface of the back-iron. These magnets interact with the magnetic field generated by the coils in the stator to generate torque. The back-iron provides a closed flux path to ensure there is no stray magnetic field outside the rotor.

A brake disc is bolted to the outside of the rotor to provide mechanical braking, so the structure must be designed to withstand the worst-case forces exerted upon the rotor during braking and lateral acceleration events. The force exerted during these scenarios is dependent on the mass of the vehicle.

A magnetic ring is fitted to the inside of the rotor. This has the same number of pole pairs as the rotor drive magnets. Position sensors (sine/cosine encoder) measure the magnetic field generated by this ring to determine the rotor's angular position.

The rotor also incorporates a rubber seal to prevent ingress of contaminants into the rotor cavity. The seal is designed to lift off as speed increases to reduce wear on both the seal and the running surface.

A standard automotive bearing links the rotor and stator. The bearing carries the full load of the vehicle, so neither rotor nor stator carry forces for supporting the vehicle. As with all elements of motor design, the characteristics of the bearing are a trade-off. It must be stiff enough to ensure there is no touch down of the stator onto the rotor during high lateral acceleration events. Conversely, the drag resistance of the bearing must be as low as possible to reduce losses and maximize efficiency of the system.



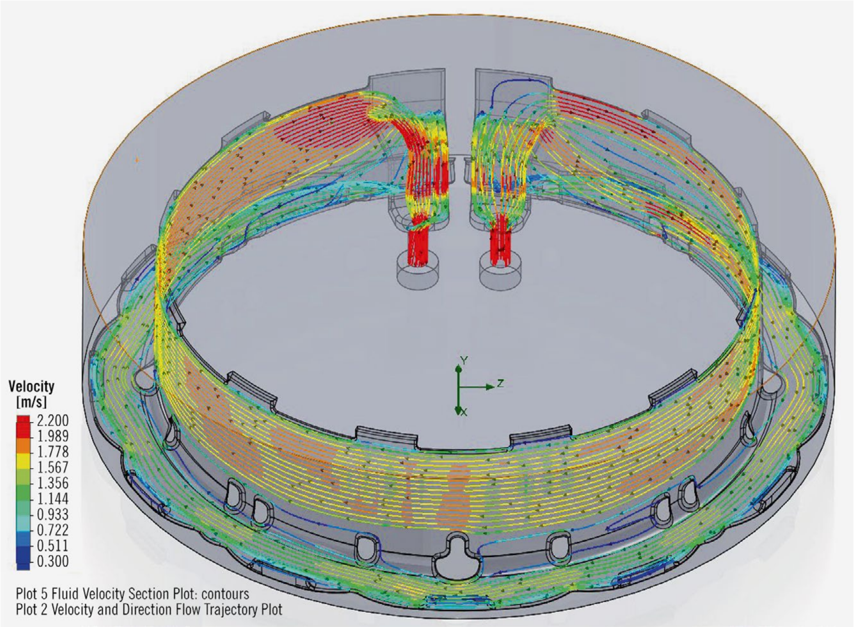


FIGURE 8 Stator cooling channels (© Protean)

The motor contains two electronic modules, each of which includes two inverters. Each module contains a processor that reads the relevant sensors and generates the signals to switch the gate drivers on and off. These in turn provide a switching signal to the IGBTs. The modules are fitted to the back of the stator and link to pins in the leadframe, which in turn connect to the coils.

Sensors required to control the inverters include the following:

- three current sensors per inverter, one per phase (twelve in total per motor)
- one position sensor per module (two in total per motor)
- three coil thermistors per inverter, one per phase (twelve in total per motor)
- two IGBT thermistors per phase (twenty-four in total per motor)
- one bus voltage sensor per inverter (four in total per motor).

MOTOR CONTROL

The inverters in the motors use Field Oriented Control (FOC). This method controls the stator currents using vector techniques. The algorithm transforms a three-phase system (typically referred to as U, V and W), in which the three phase currents vary sinusoidally with time, into a two coordinate (referred to as D and Q) system, where the currents are time invariant at a particular torque point. This effectively translates the problem of controlling three alternating currents into one for controlling two (mostly) independent direct currents.

In simplistic terms, the current in the Q axis is proportional to torque. The D axis current is the flux component; this term becomes important at motor speeds where the back-Electromagnetic Force (EMF) generated by the magnets in the spinning rotor begins to exceed the DC bus voltage. The D axis current counteracts the back-EMF in a technique known as flux weakening.

FOC relies heavily on two transforms, namely the Park-Clarke Transform, which converts the three phase currents (U, V, W) to two dimensions (D and Q), and the inverse transform, which converts the D, Q vector back to three phases.

Once the signals have been converted to the direct current domain (D and Q), they can be controlled using traditional control techniques, such as a Proportional-Integral (P-I) loop.

A full discussion of FOC control techniques is outside the scope of this paper, but several semiconductor manufacturers provide useful introductions, such as Texas Instruments [4].

One of the challenges of FOC control is determining the amount of D and Q current required to generate a particular torque for a specific DC bus voltage and speed. A theoretical method for determining the D and Q current demands is described in [5]. The motors use a lookup table approach, taking DC bus

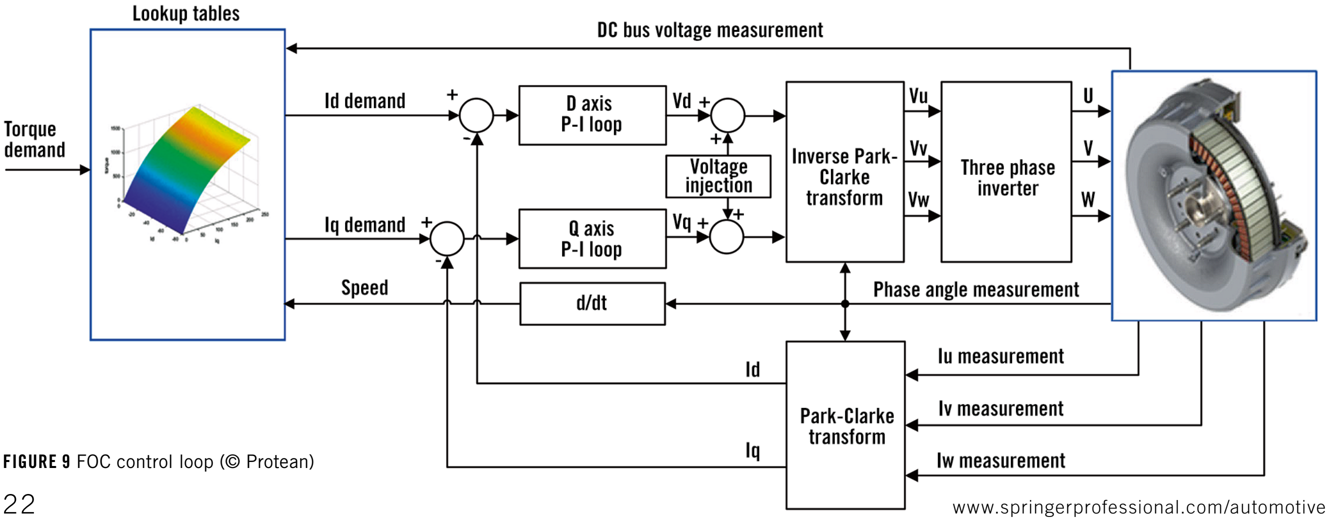


FIGURE 9 FOC control loop (© Protean)

voltage, motor rotational speed and torque demand to derive the required D and Q current demands.

The compact design of Protean Drive results in a motor that includes harmonics of the electrical frequency in the back-EMF. These interact with the fundamental phase currents to create torque ripple. To cancel this undesirable effect, the controller injects voltages in the output of the P-I loop to cancel out the disturbance. The top-level control loop is shown in **FIGURE 9**.

Each iteration of the control loop takes place every 62.5 µs (16 kHz). The control frequency is a trade-off between several factors. The control loop must operate frequently enough to control the system. At the top speed of the motor (1600 rpm) and with 32 magnet pairs in the rotor, the maximum electrical frequency is 853 Hz. At 16 kHz, there are therefore approximately 19 points per cycle, which provides a good level of control. Every time an IGBT turns off or on, a small amount of heat is generated. To maximize efficiency, the number of transitions should be minimized, so a lower switching frequency is better.

NVH is a major consideration for in-wheel motors. The interaction between the switching transients and the magnets on the rotor may result in audible noise. The switching frequency must therefore be greater than the maximum frequency perceivable by the human ear, which in most adults is around 16 kHz.

CONCLUSIONS

Protean Electric has spent many years refining the design of their combined motor-inverter to produce a high torque density drive system. The result is Protean Drive, an in-wheel motor drive system offering high levels of design freedom for BEVs and Hybrids. During the development process some compromises were made and challenges were overcome.

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