Design and Dynamic Study of a 6 kW External Rotor Permanent Magnet Brushless DC Motor for Electric Drivetrains

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***Abstract*—This paper studies electromagnetic and parametric design and performance analysis of an in-wheel out-runner BLDC (Brushless Direct Current) electric motor designed specifically for automotive applications. Typical design techniques and simulation studies are applied to the BLDC motor. Specifically, design specifications such as the number of turns, winding area, and stator pole height composing the stator structure are obtained and the performance characteristics of the motor are investigated using the finite element method (FEM). Also, the outputs in terms of phase inductances, flux linkages of each stator winding and static torques for different rotor positions are calculated and evaluated. Finally, a dynamical performance analysis is performed using a physical electromechanical model the BLDC motor.**

***Keywords*— BLDC, In-wheel Electric Motor, Co-Simulation, Road Vehicles, Parametric Design, FEA, Dynamic Analysis**

I. INTRODUCTION

The dependency on fossil fuels has been steadily increasing in the past century despite the well-known fact that the resources of such fuels are limited. It is now widely accepted that such a demand growth is not sustainable. Motivated not only by the future supply concerns but also by the detrimental environmental effects of over-exploitation of fossil resources, the interest in electric and hybrid vehicle applications has been increasing rapidly in the recent years. Therefore, electric motor designs for use in such applications became topical. In most electric and hybrid car applications permanent magnet brushless DC (BLDC) motors are widely used due to their higher efficiency and operational flexibility.

There are several studies in the literature examining the performance of in-wheel motors in many aspects, particularly for vehicular applications. In an early study, D.J. Patterson stated the reason for using permanent magnet brushless direct current (BLDC) motors for vehicular applications and described the use of finite element techniques in their design [2]. In general, axial-flux motors are found to be more favorable than radial-flux motors for electric road vehicles [4], [5], [8]. Specifically, in a study by C. Versèle et al., axial flux permanent magnet (AFPM) motors were compared to radial flux permanent magnet (RFPM) motors both in simulations and experimentally [3]. Similarly, F. Caricchi et al. studied AFPMs and set some guidelines for designing high performance AFPMs [7]. In a different study, 97.5% efficiency was obtained with an axial-flux brushless DC motor configuration [6]. M. Nagato et al. studied the Eddy current (EC) losses in the rotor surfaces [1] where he attained some conclusions on factors affecting the EC. In another work S. Wu et al. analyzed ways to improve the PM wheel motor performance [9]. In this study, the performance of the motor was analyzed in four aspects: magnetization direction and pole number; no-load air-gap flux density; no-load electromagnetic force (EMF); and flux insulation. Also, Y. Honda et al. studied interior permanent magnet synchronous (IPM) motor [10], where they reached some important conclusions regarding windings; particularly mentioning "concentrated winding is inferior to distributed winding both in terms of generated torque and constant power region size".

In this paper, an in-wheel out-runner electric motor design is made for electric vehicle applications. Particularly, the specific design aims to be used in electric vehicle conversions of existing cars. The reason for this is that, this specific design can be easily used as part of a hybrid vehicle conversion kit for converting regular cars into the parallel hybrid structure for improving fuel economy. In this way, an alternative electrification option of the existing vehicle fleet can be realized at much lover costs. This electric motor design differs from existing in-wheel motors mainly in that, it can be placed in the space between the wheel rim and the drum brake housing on the rear axle, without requiring any modifications in the existing brake system. The design of a 6 kW in-wheel on-drum BLDC motor is shown in various illustrations in the remainder of the paper.

The characteristics of the in-wheel, on-drum BLDC electric motor are shown in the figures and graphs which were obtained as a result of the parametric and co-simulation design studies using a finite element analysis program. The resulting motor performance and design parameters are presented.

II. PROPOSED MACHINE AND SIZING EQUATIONS

A. Design Considerations

Brushless Direct Current Motors (BLDCs) have miscellaneous mechanical and electrical characteristics such as

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high efficiency, high torque to weight ratio and brushless construction. In addition to this, it is important to know which design or configuration type is to be used in an electrical machine as well. Also, it is very important to consider operating temperature, homogenous magnetic field, and weight constraint and space limitation during the application of the design process. Taking these considerations into account, it was identified that an outer motor configuration for placing the system in the space between the wheel rim and drum brake housing is a good idea.

M250-35A silicon steel sheets of which magnetic properties are presented in Table 1 [11] are generally used in special motor design applications. The background to use such kind of steel sheets is due to the fact that the volume is high and the performance of the system is as important as cost.

TABLE I. M250-35A MAGNETIC SILICON STEEL CHARACTERISTICS

Loss at 1.5 T and 50 Hz		2.35 W/kg
Loss at 1 T and 50 Hz		0.98 W/kg
Anisotropy of Loss		10%
Coercivity at DC		40 A/m
Relative permeability at 1.5 T		660 H.m^{-1}
Resistivity		55 μΩcm
Magnetic Polarization at 50 Hz	H=2500 A/m	1.53 T
	H=5000 A/m	1.64 T
	H=10000 A/m	1.76 T

In the design, the parameters such as current density and specific loadings are generally recommended as 4-10 A/mm^2 and 25000-35000 A/m for permanent magnet motor applications, respectively, based on the cooling method. These design parameters for the calculation of main dimensions and flux/pole ratio has been chosen according to the initial design table as recommended in [12].

TABLE II. INITIAL DESIGN PARAMETERS

Pair of poles	20
Rated speed at 50 Hz	150 rpm
Number of phases	3
Slots per pole	1.2 (24 slots/20 poles)
Air gap length	1 mm
Outer diameter	368 mm
Max stack length of the motor	30 mm

Once these parameters have been chosen based on design procedures, the limitations and restrictions must be considered as well. The main limiting parameters (herein indicated as initial design parameters) for the specific application are presented in Table 3.

TABLE III. INITIAL DESIGN PARAMETERS

Pair of poles	20
Rated speed at 50 Hz	150 rpm
Number of phases	3
Slots per pole	1.2 (24 slots/20 poles)
Air gap length	1 mm
Outer diameter	368 mm
Max stack length of the motor	30 mm

B. Analytical Computations

According to basic dimensioning procedures [13] of outer rotor BLDC motors, and with reference to the graphical representation given in Fig.1, stator outer diameter can be calculated from;

$$D = D_{rc} - 2l_m - 2\delta \tag{1}$$

where D is the stator outer diameter, D_{rc} is the rotor inner diameter, l_m is the magnet thickness and δ is the air gap length of the motor. b_{ss1} is the upper slot opening parameter and is calculated by;

$$b_{ss1} = \pi \frac{D - 2h_{sw}}{Q_s} - b_{ts} \tag{2}$$

where h_{sw} indicates the tooth thickness of the stator core, b_{ts} is the tooth width of the core and Q_s expresses the stator slot number. And b_{ss2} gives the lower slot opening parameter and can be calculated as;

$$b_{ss2} = \pi \frac{D - 2h_{ss}}{Q_s} - b_{ts} \tag{3}$$

The parameter h_{ss} given in the last equation denotes the slot length. h_{sy} expresses the effective core thickness and can be derived as from equation (4).

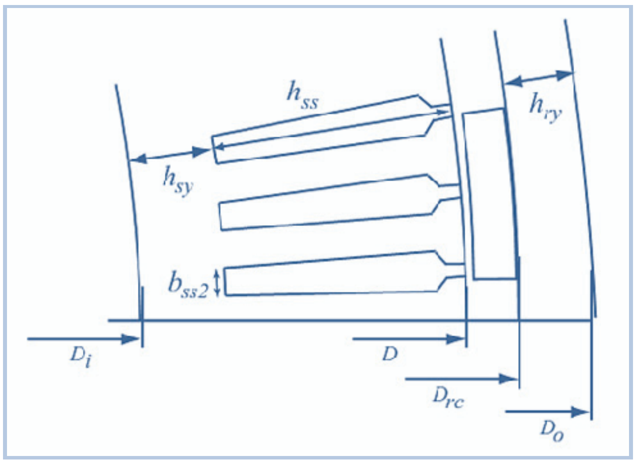

Fig. 1. Basic dimensioning of outer-runner rotor BLDC motors.

$$h_{sy} = \frac{1}{2}(D - D_i - 2h_{ss}) \quad (4)$$

In this relationship, D_i parameter indicates the inner diameter of the stator that can only be used in the design of outer-runner BLDC motors.

In order to ensure the magnetic flux linkage on the rotor, the thickness of the core is made from ST-37 steel, where the thickness can be formulized as;

$$h_{ry} = \frac{1}{2}(D_0 - D_{rc}) \quad (5)$$

Total slot area A_{sl} is given with the equation below;

$$A_{sl} = \frac{1}{2}(b_{ss1} + b_{ss2}) * (h_{ss} - h_{sw}) \quad (6)$$

Moreover, the ratio of stator slot opening to slot width is another important parameter that must be considered in the conceptual. This is computed from;

$$k_{open} = \frac{b_{so}}{b_{ss1}} \quad (7)$$

The parameters given above are used for the calculation of mechanical parameters of the BLDC motors in order to get a uniform magnetic force between rotor and stator for any rotating position. Besides, the electrical and magnetic parameters must also been considered. B_m, which is the maximum value of magnetic flux can be calculated as;

$$Bm = \frac{B_r k_{leak}}{1 + \frac{\mu_r \delta k_C}{l_m}} \quad (8)$$

where B_r indicates the permanent flux density of the magnet, μ_r is the relative magnet permeability. k_C shows the Carter factor and formulated with the following equation [5];

$$k_C = \frac{T_s}{T_s - \frac{\left(k_{open} b_{ss1}\right)^2}{b_{ss1} k_{open} + 5\delta}} \quad (9)$$

where T_s ,which is the stator tooth opening and the common parameter in both outer and inner-runner BLDC motors can be indicated as;

$$T_s = \pi \frac{D}{Q_s} \quad (10)$$

By using the above equations, the electromechanical parameters of the 6 kW outer-runner, on-drum BLDC motor have been determined. The analytical results are presented in Table 4 and also the 3D representation of the designed motor is shown in Fig.2.

TABLE IV. BLDC ANALYTICAL CALCULATION RESULTS

Rated Output Power	6 KW
Rated Speed	1100 rpm
Operating Voltage	60 V
Efficiency	~ %92
Number of Poles	20
Operating Frequency	50-200 Hz
Rated Torque	54 Nm
Rotor Material	ST37 Steel
Stator Inner Diameter	277 mm
Rotor Outer Diameter	368 mm
Stack Length	30 mm
Type of Operation	Direct Drive
Magnet Temp	150 °C
Rotor Type	Ni Coated N40SH Type Neodymium Permanent Magnets)
Ball Bearing Type	SKF/FAG Ring
Total Weight of Stator and Rotor	~ 11 kg

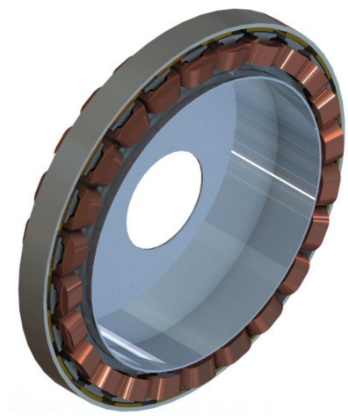

Fig. 2. Designed 6 kW BLDC outer-runner motor.

III. MAGNETIC FIELD ANALYSIS BASED ON FINITE ELEMENT ANALYSIS (FEA) AND CO-SIMULATION

Finite element method (FEM) is applied for optimizing the construction during the electrical machine design procedure. FEM is composed of many methods and sub-modules and which can help the designer to shorten the development period before the real model is built.

Since transient analysis which is the basic analysis component of finite element method is dependent on time and computes the circuit as a function of time for a given or predefined time range, it has been used for the check up on analysis algorithms, control options with different initialization parameters while designing 6 kW, 60 V BLDC motor. For a given 100 millisecond transient interval, 6 kW BLDC motor is analysed per 1 millisecond and exposed results have been presented.

The tasks accomplished can be summarized as follows;

- In order to determine distribution of the magnetic flux in stator, stator windings rotor and magnet, a 2D simulation model has been derived.
- Also, the electromechanical parameters like electromotive force, torque and stator resistance and inductance are obtained from the model. Electric machine modelling and numerical methods to solve them has been realized by using ANSYS Ansoft EM 2014 package. Some quantities such as magnetic flux density has been calculated and visualized as seen in Fig.3.
- Furthermore, a Simplorer/Maxwell Co-simulation model (Fig.4) for the analysis of motor performance in dynamic conditions is developed and results are given.

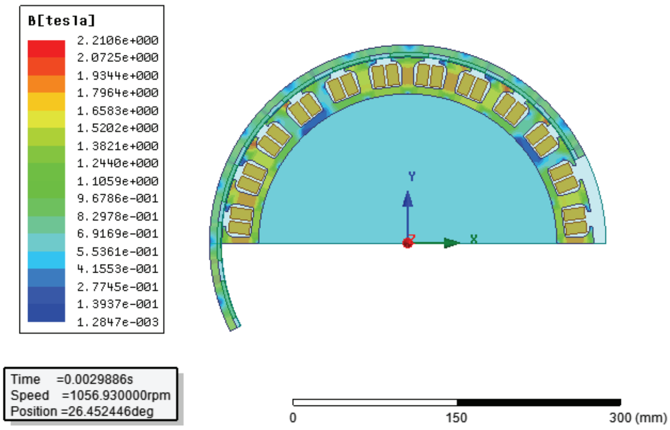

Fig. 3. Variation of magnetic field density at 3 ms while the motor is rotated at approximately 1057 rpm.

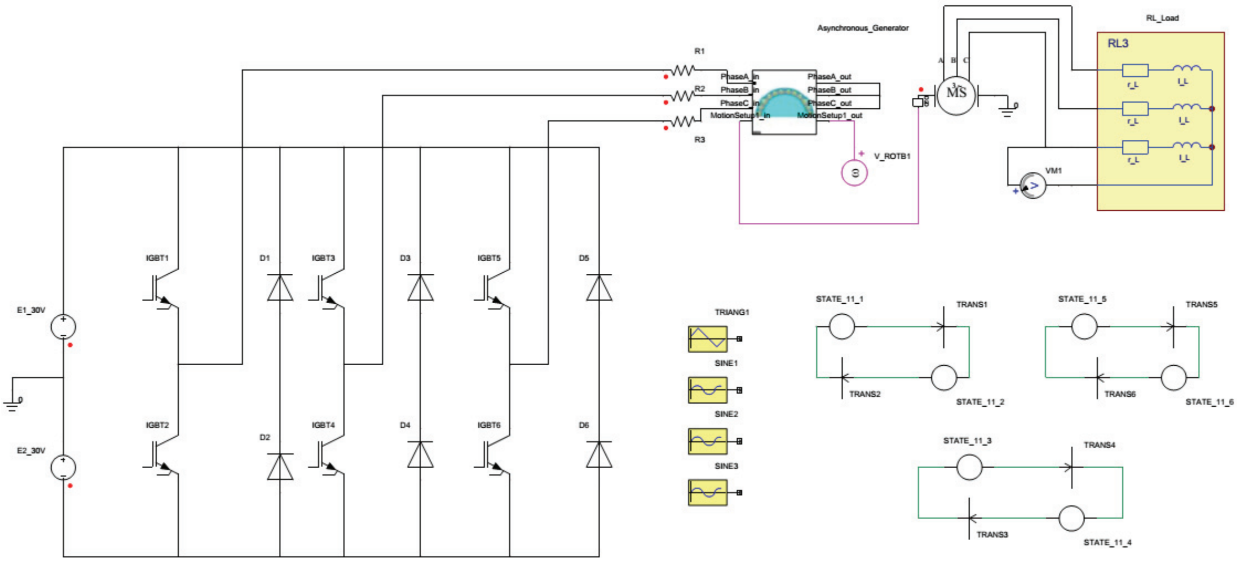

Fig. 4. Simplorer-Maxwell co-simulation.

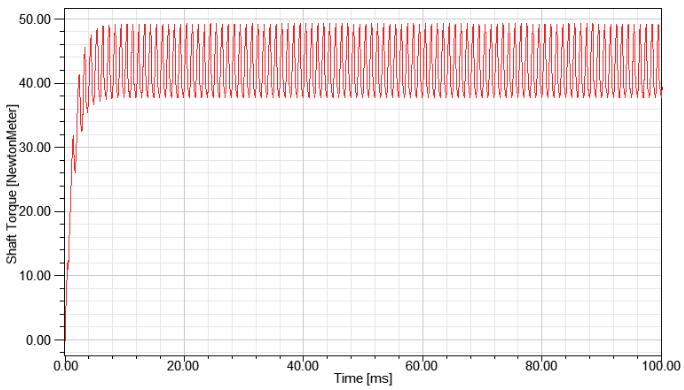

Fig. 5. Variation of shaft torque dependent on time derived by Simplorer/Maxwell Co-simulation.

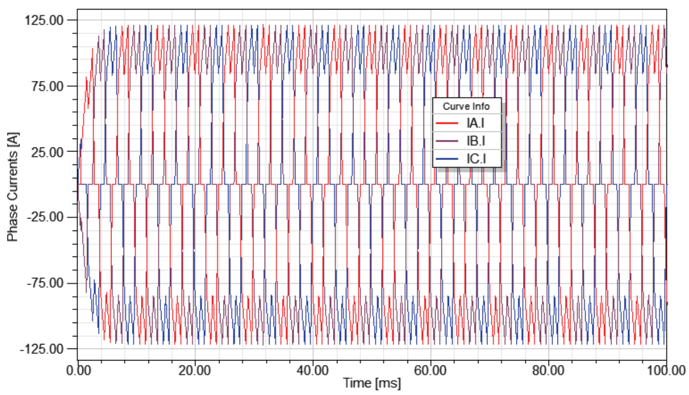

Fig. 6. Variation of phase currents dependent on time derived by Simplorer/Maxwell Co-simulation.

IV. DYNAMIC STUDY OF THE BLDC MOTOR

A final design consideration of the motor is the analysis of the dynamic analysis of the motor. For this a physical electro-mechanical model of the motor was implemented in Matlab-Simulink Environment. The screenshot of the model is seen in Fig. 7 below.

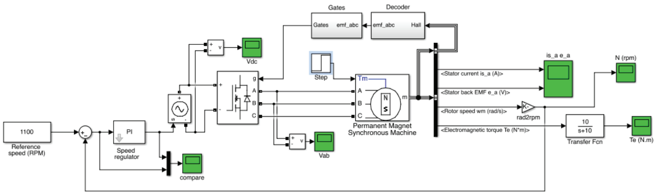

Fig. 7. Electro-Mechanical Matlab-Simulink model.

In the simulation, the motor model is implemented with the parameters obtained as the result of the design process described earlier. The motor model is then fed with a six-step inverter model. In the simulation the reference speed was taken as the rated rpm, which is 1100. According to the design scenario, a torque reference signal of 30 Nm is given to the motor at 5 seconds and the simulation was run for 10 seconds. The resulting simulation outputs are seen in Fig. 8 below.

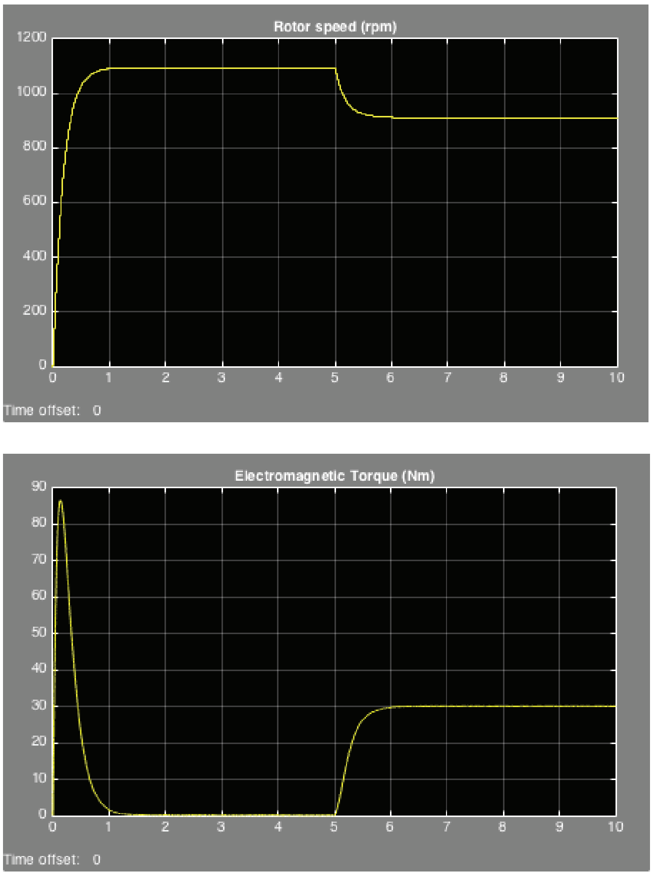

Fig. 8. Electro-Mechanical Matlab-Simulink model results.

The result of the dynamic simulation indicates that the motor performs per expectations with the design goals. Consequently, the torque and speed responses were all found to be satisfactory.

V. DISCUSSION AND CONCLUSION

In this paper, an outer-runner BLDC motor is proposed for electric vehicle propulsion that is specifically designed for use electric vehicle conversions of existing cars. The unique BLDC design has remarkable features from existing technologies in that it can be placed in the enclosure between the wheel rim and drum brake housing.

First of all, the topology of the machine and operation principle is introduced in a comprehensive way, and the sizing equations are developed for the preliminary design. Based on the developed analytical model, 6 kW BLDC motor is designed, simulated and validated by using 2D parametric approach method of which results are demonstrated in Fig.10 in a comprehensive way and then it is composed to 2D Simplorer/Maxwell Co-Simulation which was derived by coupling a 3 phase asynchronous generator and applying 6 kW rated load. It was observed that transient analysis results were satisfactory.

Moreover, stator part of the developed 6 kW BLDC motor was manufactured as seen in Fig. 9.

Fig. 9. Manufactured stator of 6 kW BLDC motor.

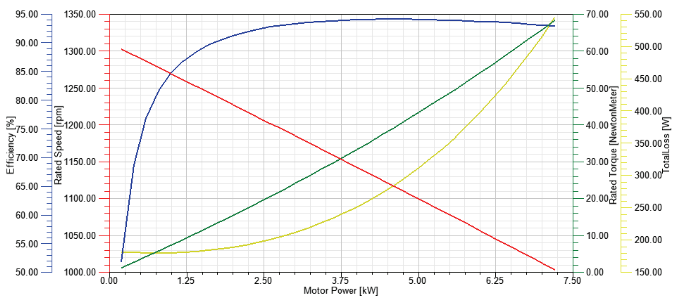

Fig. 10. Results derived from parametric approach method in ANSYS RMxprt.

In fact, the study on 60 V, 6 kW, in-wheel, on-drum BLDC electric motor is not yet complete. Testing, verification and advanced analysis studies need to be performed. Future studies going to focus on eddy current loss minimization in permanent magnets as well as copper loss optimization in stator windings as studied in [14-17]. Also load tests will be carried out by coupling the motor in the enclosure between the wheel rim and the drum brake housing, where it will be tested for performance to assess whether the design is suitable as part of an electric car conversion kit. The new design has been compared with a commercial in-wheel electric motor designed and manufactured by Protean Company. The differences of both designs can be evaluated in Fig.11 and 12. It is clear that new in-wheel electric motor is specifically designed for the use electric vehicle conversions of existing cars. Since the design is suitable for placing in the enclosure between the wheel rim and drum brake housing, it differs from existing technologies.

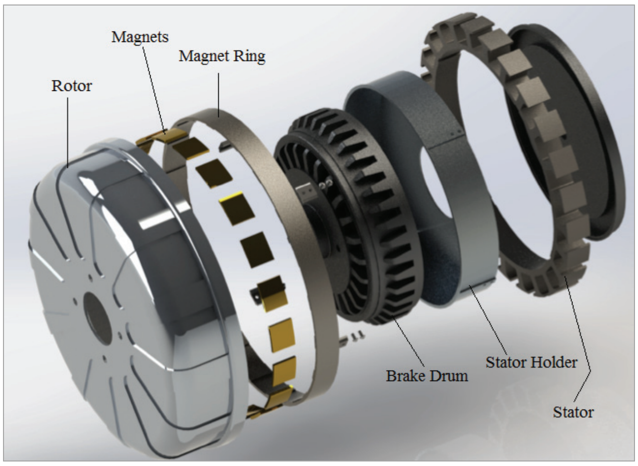

Fig. 11. On-drum in wheel BLDC electric motor design to be prototyped.

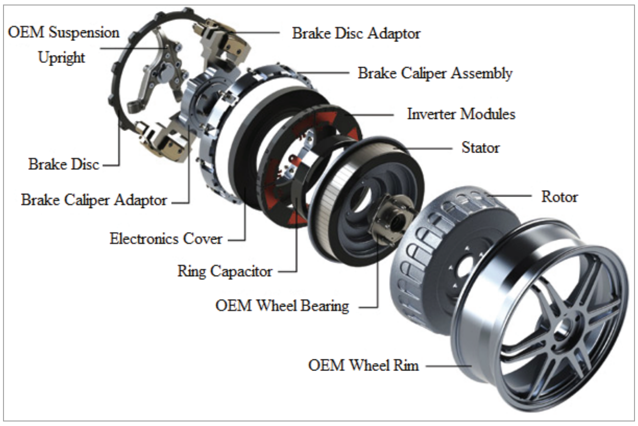

Fig. 12. A commercial in-wheel electric motor by Protean Company.

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