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ANALYSIS AND IMPROVED DESIGN OF DIRECT-DRIVE CORELESS AFPM IN-WHEEL MACHINE FOR HEV APPLICATION

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Abstract- This paper illustrates the design of in-wheel direct-drive axial flux permanent magnet (AFPM) machine for hybrid electric vehicle (HEV) in order to obtain a wide speed range operation with high operation efficiency and low cogging torque. Using a coreless type of stators can help to improve the total machine efficiency as a result of power loss reduction. In order to achieve the direct drive without any mechanical transmission for HEVs, the wheel motor has been designed as a low-speed high-torque motor. Direct drive, in-wheel motors are ideal for vehicles, because of their high efficiency, compressed packaging, easy handling, and safety operation. The performance analysis of this axial flux permanent magnet in-wheel motor is done using finite-element method and the obtained results verify the validation of this proposed design method. The experimental results obtained from sample practical prototype, confirm the analytical method.

Keywords: Hybrid Electric Vehicles (HEV), Direct-Drive, In-Wheel, Axial Flux Permanent Magnet (AFPM).

I. INTRODUCTION

The anxieties about the world petrol and gas reserves and their prices, as well as pollution and global warming issues have increased the interest on electric and hybrid vehicles. The governments have started to assign more encouraging facilities and, professional companies have focused on electric and hybrid vehicle development projects. In the last decade studies, main attention was concentrated on series and parallel hybrid vehicles.

The hybrid electric vehicles (HEVs) on the market today are primarily parallel hybrids in which the drive power for the vehicle is supplied by both an internal combustion engine (ICE) and a set of electric machines [1, 2]. A different system design is the series HEV. In this type, the ICE is disconnected from the drive-train and the electric machines provide all drive power to the vehicle wheels. Permanent magnet (PM) machines have been widely used for EV and HEV applications. This is due to having inherently more efficiency than other electric machines because of their permanent magnet (PM) excitation.

An axial flux PM machine (AFPM) benefits such as simplified construction, their compact design, high power density, high efficiency, superior torque density, possibility to add a high number of poles, very low rotor losses and adjustable axial air gap, produces a machine that is efficient and compact and is therefore ideally suited for use in vehicle. Also using a coreless type of stators can help to improve the total machine efficiency as a result of power loss reduction [2-4]. Moreover, due to its inherently short axial length, it is suitable for the electric traction machine as in-wheel direct-drive motor. But in the direct-drive traction system, mechanical power transmission compartments are eliminated and therefore the volume and weight of the whole drive system is reduced as well as the transmission losses are minimized.

Moreover the drive system is simplified and its operation efficiency is improved. So it can be said using in-wheel motor for direct drive instead of conventional motor drive with mechanical power transmission gears, is the future direction of motor drive system for HEVs. There is no mechanical transmission system between the wheel and electric motor in such a direct-drive power train system, and electric machine is directly connected and coupled to the wheel, therefore electric machine and wheel have the same torque and speed [5, 6].

It has been demonstrated by the previous works, in the last ten years, if the number of poles in the AFPM machines is large enough and the axial length sufficiently small, their torque density is considerably larger than that obtained by traditional radial flux machines [20]. Moreover, due to the relatively small speed of the wheels, with a large number of poles, using AFPM machine as a gearless in-wheel drive is feasible [7-10]. In addition high torque density and high efficiency are necessary for a vehicle with an in-wheel direct-drive system and also such vehicle propulsion system requires low cogging torque and wide range of constant power speed.

These issues need to be considered during the design procedure of the AFPM machines for the direct drive HEV application as in-wheel machines. In this paper, a novel low-speed coreless AFPM machine for an in-wheel gearless drive of HEV is proposed and the analytical design procedure to achieve high efficiency at the vehicle's various speeds is presented.

The AFPM has a three-phase winding which can produce a rotary magnetic field in the air gap [19]. This type of electric machine can provide high-power density at low speed and, hence, it is acceptable to use as a direct drive in HEVs [10, 11]. Both analytical and three-dimensional electromagnetic finite element analysis (3D FEA) models are employed to calculate the parameters of the machine. Moreover, the FEA is used to further analyses and optimize the machine performance.

II. ELECTROMAGNETIC DESIGN AND ANALYTICAL MODELING

A. Torque Calculation

By using Fleming's rule, the force produced by the stator current and PMs in rotor disk is calculated as follows [12-15]:

$$dF_x = I\left(dr \times B_g\right) = A_{(r)}\left(dS \times B_g\right) \tag{1}$$

where, there is expression I is used as the stator's equivalent current. It is calculated from the following equation:

$$Idr = A_{(r)}ds \quad , \quad \sqrt{2}A_{(r)} = A_{m(r)} \tag{2}$$

where, dr is the differential radius and ds is the differential surface in the rotor disk. $A_{(r)}$ and B_g are the electric loading and the vector of the axis-component of airgap flux density at a value of any differential radius r, respectively. The peak value of the stator current density, $A_{m(r)}$, is obtained from Equation (3). This value is also known as specific electric loading and is evaluated as:

$$A_{m(r)} = \frac{\sqrt{2}m_1 N_1 I}{\pi r} \tag{3}$$

where, N_1 and m_1 are the number of winding coils per phase, and the number of current phases, respectively. Using Equation (1), the produced electromagnetic torque in the AFPMs is expressed as:

$$dT_{em} = rdF_x = 2\alpha_i m_1 N_1 k_w I B_g r dr \tag{4}$$

where, k_w is the winding factor and a_i is the magnetic field factor in the air-gap (in sinusoidal wave $a_i = 2/\pi$). It is assumed that the machine has the regular airgap flux density, B_g, in the axis-direction. Therefore, the resulting equation from (4) is given by:

$$T_{em} = 0.25\alpha_i m_1 N_1 k_w I B_g\left(D_o^2 - D_i^2\right) \tag{5}$$

where, D_o and D_i are the outer diameter and the inner diameter, respectively.

B. Back EMF

The flux per pole in the proposed AFPM motor is given by:

$$\Phi_{pole} = \alpha_i \pi \frac{\left(D_o^2 - D_i^2\right)}{4}\frac{B_{mg}}{2p} \tag{6}$$

where, p indicates the number of magnetic poles and B_{mg} is the maximum airgap flux density. The RMS value of the induced *EMF* in each phase, E_f, is equal to:

$$E_f = \sqrt{2}\pi n_s N_1 k_w B_{mg}\frac{(D_o^2 - D_i^2)}{8} \tag{7}$$

where, n_s is the number of cycles per second.

C. Air Gap Flux Linkage and Air Gap Flux Density

The air gap flux linkage, Φ_g, is generally defined as:

$$\Phi_g = \sqrt{\left(\Phi_m + L_d I_d\right)^2 + \left(L_q I_q\right)^2} \tag{8}$$

where, Φ_m is the flux that provided with permanent magnets, and L_d and L_q are machine's d and q-axis inductances respectively. Hence L_dI_d and L_qI_q are fluxes produced by the stator's d and q-axis currents [9]. The airgap flux linkage is given by the following equation:

$$\Phi_g = k_w N_1 B_g \frac{\left(D_o^2 - D_i^2\right)}{2} \tag{9}$$

where, B_g is the airgap flux density and is defined as:

$$B_g = \sqrt{\left(B + B_d\right)^2 + B_q^2} \tag{10}$$

where B is the flux density produced by PMs, B_d and B_q are the total flux densities that provided with stator's d and q-axis currents, respectively.

III. OPTIMUM SIZE OF THE AFPM

Some constraints, such as flux saturation, type of structure, thermal constraints, limited available space in the vehicle wheel, various PMs inherent specifications, maximum current density of used conductor, and the driving voltage, should be considered to achieve required specifications in the proposed motor design. In other words, the motor optimization method is a multifunctional scheme and with this method the requested in-wheel motor is designed and analyzed.

To achieve the requested driving voltage and to induce the larger back electromotive force to the windings, the coils are independently wired on stator poles and are grouped into required phases. With this method the higher motor speed is reached and multiphase machine structures can be constructed. Therefore, the effects of the number of phases can be studied on the machine total efficiency. Other specifications of the motor are listed in Table 1.

Table 1. Specification of direct-drive electric wheel Motor

Objectives	Low-speed, High-torque
Rated torque	> 30 Nm at 420 rpm
Max. torque	> 60 Nm at 130 rpm
Rated power	3 kW
Rated speed	420 rpm
Vehicle max. speed	100 km/hr
Acceleration	5 seconds for 20 m/sec
Driving slope	> 8° at 15 km/hr
Motor weight	< 15 kg
Operation temp. range	0°C ~ 40°C

To introduce the size and characteristics of vehicle tire, the phrase P*www*/*hh*R*dd* is used. In this expression, P and R denote passenger tire and radial tire, respectively, *www* is the tire width in mm, *hh*, as a percentage of *www*, is the height of the side wall, and *dd* is the inside diameter in inches. In this application the tire size of P205/50R17 is selected to use in vehicle. The outside circumference of this tire is 2 m.

There are some important parameters that affect the design of AFPMs. In these parameters the diameter ratio, D_i/D_o, and air gap flux density are the two design variables having more effect on the machine inherent characteristics. Therefore, in order to find the best performance of the desired AFPM and the machine's optimum size, the diameter ratio and airgap flux density must be designated intently [17, 18].

The maximum motor efficiency is occurred at the maximum power density. To achieve the maximum power density of the machine and to determine design features many different structures must be analyzed. In this paper a software package is used for FEM method that enables analysis and optimization to do faster, more effective and simple. This software is an excellent supplement to analytical methods, especially when considering geometry details and variations in the machine construction.

In this programming method a multifunctional optimization method is used to search the optimal values of the design variables that maximize the following performance indices such as motor torque, torque or power density and overall efficiency. Design constraints for a HEV application are also included in the program. In the package, desired performance indices are weighted under the constraints, to reach a satisfactory compromise among the design variables.

Figure 1 shows the power density variation as a function of air-gap flux density and the diameter ratio for the AFPMs as expressed in equation (9) and (10). As can be seen from this figure, the maximum power density (or torque density) occurs at an air gap flux density of 1.2 T and a diameter ratio of 0.62. From this figure, the maximum power density is found to be 5.2 W/cm^3.

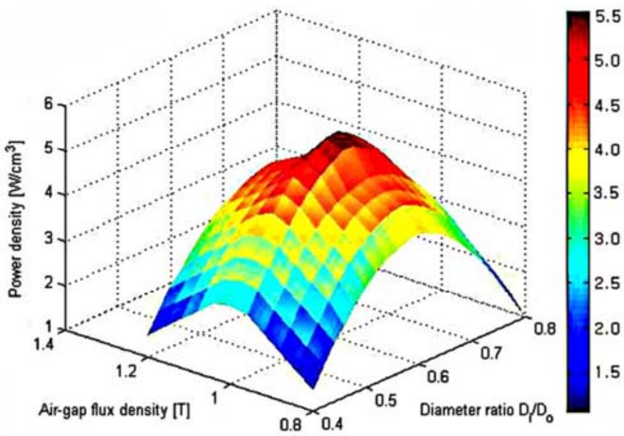


Figure 1. Power density of AFPM vs air gap flux density (B_g) vs diameter ratio (D_i/D_o) [2]

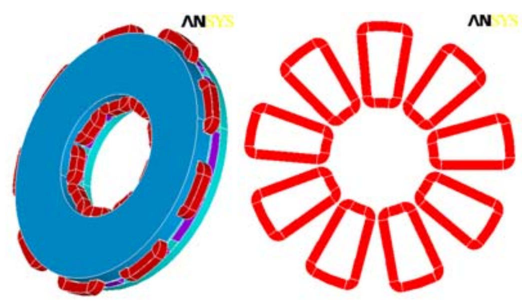
The motor parameters of the three phases from the optimal design and the technical data are listed in Table 2. Since the coils are independently wired on stator poles, three parallel coils are grouped into one phase for each side of the stator of this motor. Further investigation on the motor performance by the finite element method becomes necessary for the final decision.

Table 2. Motor characteristic obtained from magnetic analysis & optimization

parameter	value
Max. current per phase	19.8 A
Rated torque	33.2 Nm
Max. torque	62.1 Nm
Flux density	1.22 T
Motor weight	11.2 kg
Rated voltage	48 V dc
Max. torque density	5.54 Nm/kg
Air gap length	2 mm
Number of rotor poles	12
Number of stator coils	9
Outer diameter	22.5 cm
Inner diameter	14 cm

IV. CONFIGURATION OF AFPM MACHINE

Flux in an axial flux machine flows through the air gap axially. Axial flux PM machines have discs for the rotor and the stator geometry. The proposed axial flux PM in-wheel machine configuration in this paper is shown in Figure 2(a). Figure 2(b) shows the winding configuration in this machine. This is a three-phase AFPM machine with one rotor and a coreless (ironless) stator configuration. The stator core is made by epoxy resin and windings are inserted in the stator core. The stator has a set of three-phase ac windings. Owing to their ease of fabrication and assembly concentrated armature coils are employed to generate nearly sinusoidal voltage output. Figure 3 shows the 3D disassembled view of the medium-speed coreless surface mounted AFPM motor under study, which consists of one rotor disc and one stator disc. PMs are glued to the surfaces of solid mild steel rotor disc. A sintered neodymium-iron-boron (Nd-Fe-B) material is selected as the best candidate for the permanent magnets in the rotors. Coreless axial flux permanent magnet machines have been extensively studied because of additional advantages of their enlarged air gap leading to low synchronous reactance, cogging torque free, high power factor and higher efficiency as a result of absence of core losses in the stator.



(a) (b)

Figure 2. (a) An AFPM assembled view, (b) Winding configuration of proposed AFPM

Coreless AFPM machines are also used for various power generation applications particularly in direct-drives over a wide operational speed range. For instance, coreless AFPM machines are investigated for low-speed applications for direct-coupled wind turbine generators and medium speed applications for automotive generators. No rotor copper losses due to permanent magnet excitation and no stator eddy current losses in the ironless stator lead to high efficiency in proposed AFPM machine.

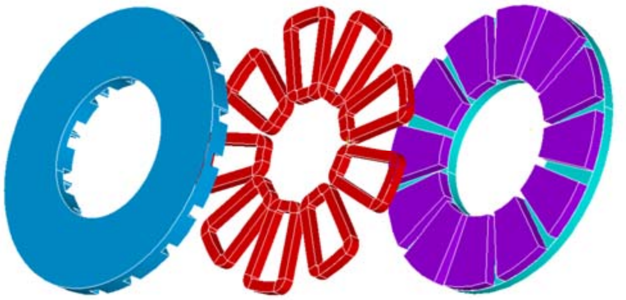


Figure 3. An AFPM disassembled view

V. LOSS CALCULATION

One limiting parameter in the machine design is the power losses. The loss calculations are only briefly described here, as follows [11, 13]:

1. Rotation losses are the main losses in the machines. Air friction losses (rotational losses) are dependent on g (air gap) and D_o (outer diameter). Calculations of this power loss are considered in many papers. The power required to overcome drag resistance of a rotating disc is:

$$P_{mech} = 0.0311\left(\frac{2g\times 10^{-3}}{D_o}\right)^{-0.25} \mu^{-0.25}\rho^{0.75}\left(\frac{2f}{p}\right)^{2.75}\left(\frac{D_o}{2}\right)^{4.5} \quad (11)$$

where, μ and ρ are the efficiency and air density, respectively and f is the frequency of rotor.

2. Stator winding losses in the specific load current (I_{load}) are obtained by the simple equation:

$$P_{cu} = R_s I_{load}^2 \quad (12)$$

where, R_s is the stator winding resistance.

3. The frequency of the magnetic field causes additional losses in the stator (eddy-current losses):

$$P_{eddy-cu} = \frac{(2\pi f B_g D_{strand}\times 10^{-3})^2}{32\rho_{cu}} V_{cu} \quad (13)$$

where, D_{strand} is the diameter of each wire of conductor. ρ_{cu} and V_{cu} are Electrical resistivity and volume of copper (winding), respectively.

In order to calculate the spinning loss with described method the machine was operated using an uncut steel toroid as the stator piece [4]. The core loss in the machine with uncut steel toroid stator in the rated values is about 28 watts. If the effects of stator slotting are to be considered the total core loss in the iron cored stator is more increased. But with a coreless stator this loss is neglected and the total efficiency is increased as shown in Table 3. Figure 4 represents 2D view of flux density distribution in the designed AFPM that used to core loss calculations.

Table 3. Comparison of obtained results

Parameter	FEM Results		Experimental results
	Coreless stator	Iron core stator	Coreless stator
Rated output torque at rated speed (Nm)	33.2	35.1	32.4
Total machine loss (W)	42.3	71.7	64.9
Efficiency (%)	97.1	95.3	95.5

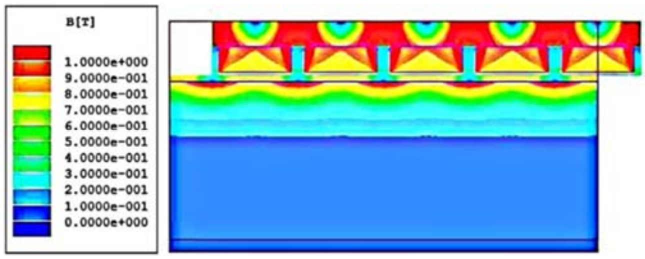


Figure 4. 2D view representation of the stator flux densities present in the test machine when the stator is replaced with an uncut steel toroid

VI. PROTOTYPE AND EXPERIMENTAL VALIDATION

The AFPM is modeled by using 3-D finite-element method (FEM). The prototype motor based on the designs previously discussed have been fabricated and tested as illustrated in figures. The coils, stator, rotor and their assembly are provided in Figures 5-7. The total losses calculation results of the designed machine with two types of stators are presented in Table 3.

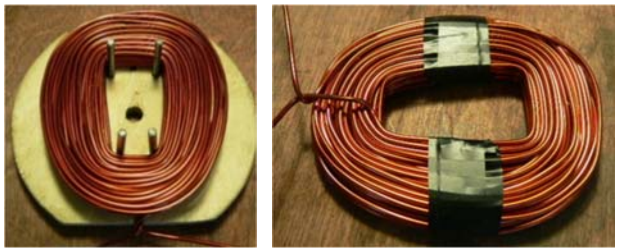


Figure 5. Stator coils assembly

Figure 6. Stator and rotor assembly

It can be shown that for this in-wheel drive in electric vehicles, the coreless AFPM produces about 2% higher efficiency when compared to iron cored AFPM. If additional costs of iron cored stator manufacturing are considered this issue becomes more prominent. The validation of design method confirmed a good agreement between the measurements and results obtained by FEM (ANSYS) from a coreless AFPM prototype.

Figure 7. Motor assembly

VII. CONCLUSIONS

The focus of this article has been to obtain the characteristic equations for the design and to find the improved sizing for the output power. The electromagnetic design has been performed by applying the characteristic equations to the type of AFPM machine. In order to optimize the machine, the power density, the diameter ratio and the air gap flux density have been chosen carefully. The machines were compared in terms of the power density and the results were applied for design of this machine. The performance analysis of this axial flux permanent magnet in-wheel machine is done using finite-element method and the obtained test results validate the effectiveness of this proposed design method. The simulated and test results show that the coreless in-wheel direct drive AFPM has a better efficiency when compared with an AFPM with iron cored stator.

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BIOGRAPHIES

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