Design of Axial Flux Permanent Magnet Brushless DC Motor for Direct Drive of Electric Vehicle

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Abstract—**Major car manufacturers such as Toyota, Honda, Ford and Hyundai are engaged in serious research, development and manufacture of hybrid electric vehicles in order to promote fuel efficient and environmentally friendly cars. Electric motor is one of the major energy consuming parts in a hybrid electric vehicle. Other than the requirement to should have high efficiency irrespective of driving conditions, the electric motor must also have high torque density and compact design. This paper presents the design of an electric motor for the direct drive of electric vehicle. A permanent magnet motor was designed in the form of an axial flux inner stator-non slot type. Preliminary design for a motor with 16 rotor poles was chosen in order to achieve high torque density and stable rotation at low speed. The motor design was simulated by using Ansoft Maxwell3D electromagnetic simulation finite element method (FEM) software to get certain parameters. The motor was fabricated and constructed on a test-bed. Data from the experimental tests were obtained and the results were compared to the simulation results.**

***Keywords*—Hybrid electric vehicle, axial flux permanent magnet motor, in-wheel**

I. Introduction

The electric vehicle (EV) in nearest future will become an excellent choice for transportation. It is generally recognized that there is a need for new methods of affordable, non-polluting personal transportation. In 1870 Sir David Salomon developed a car with a light electric motor and very heavy storage batteries. Driving speed and range were poor. Years after Sir David, in 1898, Dr. Ferdinand Porsche, at age 23, built his first car, the Lohner Electric Chaise. It was the world's first front-wheel-drive. Porsche's second car was a hybrid, using an internal combustion engine to spin a generator that provided power to electric motors located in the wheel hubs. On battery alone, the car could travel nearly forty miles.

Research and development of electric motors to find the most suitable motor for electric vehicle has been an ongoing process keenly pursued by numerous researchers and engineers throughout the world. Permanent magnet brushless DC motor has been the most popular electric motor that is being used in electric vehicle applications. Advanced power electronic technologies such as appropriate converter topology, adaptive control technique and powerful digital signal processing have made it possible to construct an efficient and compact drive system. The main advantages of permanent magnet brushless motor are compactness, low weight and high efficiency. For these reasons, a permanent magnet motor provides a good alternative for electric vehicle propulsion. Several permanent-magnet motors have been developed for electric vehicles to fulfill special requirements such as high power density, high efficiency, high starting torque, and high cruising speed.

Electric motor that is being used in electric vehicle can be classified as indirect-driven or direct-driven motor. Direct-driven motor which is designed in wheel is called wheel motor or hub-in motor. This type of motor is directly mounted inside the wheel. This drive system does not use transmission gears or mechanical differential gears for mechanical power transmission while in-direct driven motor is using mechanical power transmission system to transfer the mechanical power from the electric motor to the wheels. Mechanical transmission system contributes to additional volume, weight and power losses. The absence of mechanical transmission components in direct-drive system usually improves the overall efficiency and make the vehicle more compact.

In term of flux flow, design of electric motor can be divided to two types: the radial flux motor (RFM) and the axial flux motor (AFM). In RFM, the magnetic flux flows radially through the stator, the air gap and the rotor whereas the AFM magnetic flux flows in the axial direction. Compared to the RFMs, the AFMs can provide higher electromagnetic torque [**6**]. For direct-driven motor, an axial-flux motor has more advantages compared to the radial-flux motors. Examples include balanced motor-stator attractive forces, better heat removal configuration, and adjustable air gap. Axial flux permanent magnet motors with several configurations have been used for many high performance applications [**1, 3**]. This kind of motor can be designed for higher torque-to-weight

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ratio with high efficiency. Compared to slotted axial flux motor, non-slotted axial flux motor has low ripple torque [3]. There are a number of applications for medium and large power axial flux with external permanent magnet rotors, especially for electric vehicles. Excellent low speed performance and high torque generating capacity are inherent natures of this type of motor. These characteristics are suitable for buses and shuttles. For small electric vehicle the motor which is directly mounted in the wheel is recommended [2].

This paper presents the design and experimental work of the axial flux non-slotted surface mounted permanent magnet motor. The motor has been designed to put inside the wheel of a motorcycle.

II. Conceptual Design

The motor design procedures are discussed in the following sections. The prototype motor was designed to be fitted into the wheel of an electric motorcycle.

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A. Vehicle Dynamics

A simple vehicle dynamics model to evaluate vehicle performance is presented. A simplified vehicle model load (F_w) consists of rolling resistance (f_{ro}), aerodynamic drag (f_l), and climbing resistance (f_{st})

$$F_w = f_{ro} + f_l + f_{st} \tag{1}$$

The rolling resistance (f_{ro}) is caused by the tire deformation on the road:

$$f_{ro} = f_r \,.\, m \,.\, g \tag{2}$$

The climbing resistance (f_{st} with positive operational sign) and the down grade force (f_{st} with negative operational sign) is given by

$$f_{st} = m \,.\, g \,.\, \sin \alpha \tag{3}$$

A simulation model based on the parameters given in Table-1 has been used to evaluate the proposed axial motor and to estimate its performance up to the field weakening region. First, the required power must be computed. Starting with the definition of acceleration where F is defined as the amount of available propulsion force,

$$a = \frac{dv}{dt} = \frac{F}{m} \tag{4}$$

and integrating over a time interval t_f to a terminal velocity of v_f,

$$m \int_0^{V_{rv}} \frac{dv}{F} = \int_0^{t_f} dt \tag{5}$$

The rated power P_m can be found. The left hand side of the equation (6) can be divided into the constant torque (motor speeds up to v_{rm}) and the constant power (motor speeds from v_{rm} to v_{rv}) integrals:

$$m \int_0^{v_{rm}} \frac{dV}{P_m / V} + m \int_{v_{rm}}^{v_{rv}} \frac{dV}{P_m / V} = t_f \tag{6}$$

Now solving for the required motor power Pm, we get:

$$P_m = \frac{m}{2 t_f} (v_{rm}^2 + v_{rv}^2) \tag{7}$$

where the motor operates in the constant torque mode until speed v_{rm} is reached, and then operates in the constant power mode until terminal velocity v_{rv} is reached at time t_f. For our design to reach 50 Km/h (13.88 m/s) in 10 seconds (v_{rm} = 10m/s, v_{rm} =13.88 m/s and t_f = 10 sec). If the weight of the motor and the passenger is 120 kg, the required rated motor power P_m then depends on the ratio of v_{rm} and v_{rv}. With initial speeds v_{rm}=0, the motor power required is 1,755,9 watt. The torque required by the motor can be found using (1). The wind drag is assumed to be 0 and the vehicle travels on level road. The force F calculated is 166.5 N and with the tire radius at 0.23 m, the torque will be 38.3 Nm.

B. Motor Design

The most important parameters that need to be emphasized in order to design an electric motor are mutual torque and back EMF. Both of these parameters are linked together as stated by *BlI* and *Blv* laws. In these laws *BlI* can determine torque whereas *Blv* is to determine back EMF. When a current-carrying conductor is placed in a magnetic field, it will produce force which is called electromagnetic force. This force is fundamentally important because it constitutes the basis of operation of motors, generators and many electrical instruments. A magnitude of the force depends on the orientation of the conductor with respect to the direction of magnetic field. The force is maximum, when the conductor is perpendicular to the field and zero when it is parallel to it. The maximum force acting on a straight conductor is given by

$$F = Bli \sin \theta \tag{8}$$

where F is the force acting on the conductor, B is the flux density of the field on conductor element, l is the active length of conductor, i is the current flow in conductor and θ is the orientation of the conductor to the magnetic field.

In an axial flux machine, the length of the conductor is the difference between the outer radius, r_o and the inner radius, r_i of the stator. By assuming that the flux density does not change significantly across the sectional area of the conductor, the mechanical force, F_c acting on the conductor for a radial length can be expressed as follows

$$F_c = B_c i(r_o - r_i) \quad (9)$$

where $\boldsymbol{B_c}$ is the component of flux density perpendicular to the conductor and (r_o - r_i) is the length of the conductor.

The force on one set of coil with N_c turns of conductor is

$$F_c = 2N_c B_c i(r_o - r_i) \quad (10)$$

The mechanical torque produced from a single conductor is

$$T_c = r_m B(r_o - r_i)i \quad (11)$$

where r_m is mean radius of active winding on the rotor, define as (r_o + r_i) /2. Than, the torque due to one coil with N_c turns per coil is

$$T_{coil} = 2N_c r_m B(r_o - r_i)i \quad (12)$$

Back EMF produced by one coil of the motor during operation was calculated using relative speed of conductor (ω) to the permanent magnet and the number of turn per coil (N_c) turn of coil:

$$E_{coil} = 2N_c \omega r_m B(r_o - r_i) \quad (13)$$

From magneto static FEM simulation, the flux density can be determined. Magnetic flux line and the plot of magnetic flux density at the conductor region are shown in Fig.1. Winding coils are arranged on stator (center bar). The current injected to the winding coils is in sequence. Current carrying conductors move relatively to the embedded magnets on the rotor.

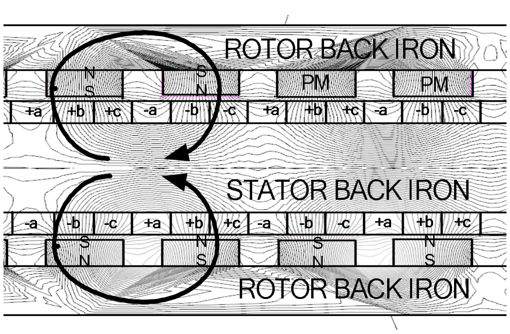

Fig.1. Magnetic flux line in the motor

III. DESIGN AND SIMULATION

An axial flux permanent magnet motor is different from a conventional electric motor due to the path of magnetic flux inside the motor. The design of the direct drive (in-wheel) motor is shown in Fig. 2. The axial flux motor is placed in a rim of the tire. Rotating parts of the motor are placed at both sides of the stator. These parts can freely rotate together with the whole wheel. In this design, the three phase windings are arranged around a ring-shaped stator.

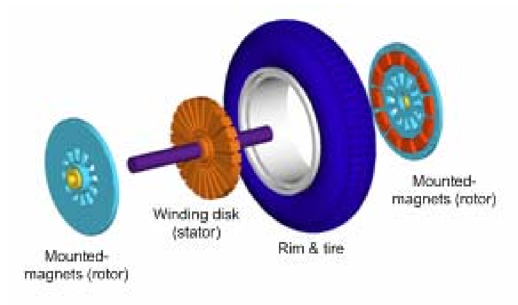

Fig. 2. In-wheel motor concept

A. Simulation Parameter

The design was simulated by using Ansoft Maxwell3D electromagnetic simulation FEM software. The simulation model managed to reach the target output (1.7 kW) required for an electric motorcycle. The simulation was conducted in the magneto static mode, which is running at every step of the rotor angle position relative to the stator. For this simulation, the input parameters that need to be considered are permanent magnet thickness, air gap width and magnetic properties of all active materials.

Figure 3 shows the simulation of the motor by using Maxwell3D software. From this simulation, the flux density which is perpendicular to the coil (B_c) can be determined.

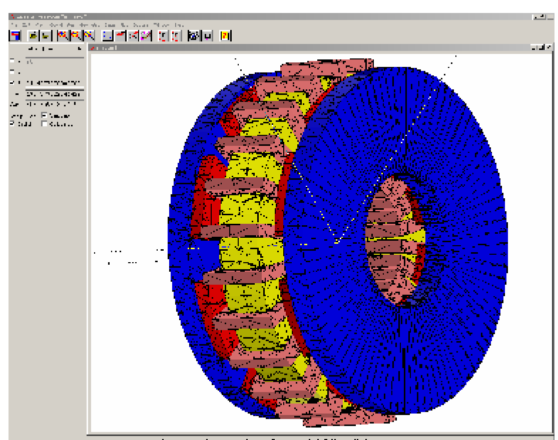

Fig 3. Simulation of axial flux motor by Ansoft Maxwell3D

The simulated values of torque and back EMF produced by the motor can be calculated by using equations (12) and (13), respectively. The simulation parameters that are stated in

Table-II have been chosen to fulfill the motor power requirement.

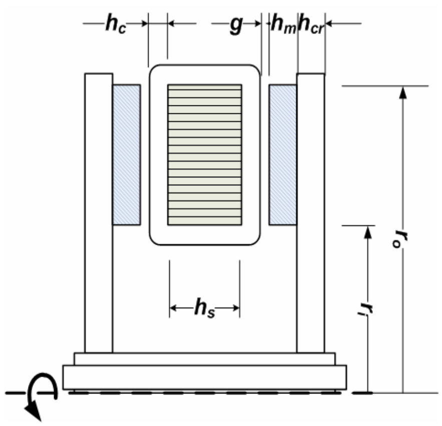

Fig.4. Main dimensions of AFM.

TABLE- I
SIMULATION PARAMETERS

Coil height	h_c
Magnet thickness	h_m
Rotor back iron thickness	h_{cr}
Stator core thickness	h_s
Rotor outer radius	r_o
Rotor inner radius	r_i
Airgap	g

B. *Results of Simulation*

Figure 5 shows the simulation torque with respect to the shaft position and Fig. 6 shows the simulation back EMF. In this simulation, at rated current of 12A and rated speed of 700 rpm, the motor can produce a maximum torque of 26N-m and a back EMF of 157V. These results show that this motor can fulfill the power requirement of an electric motorcycle.

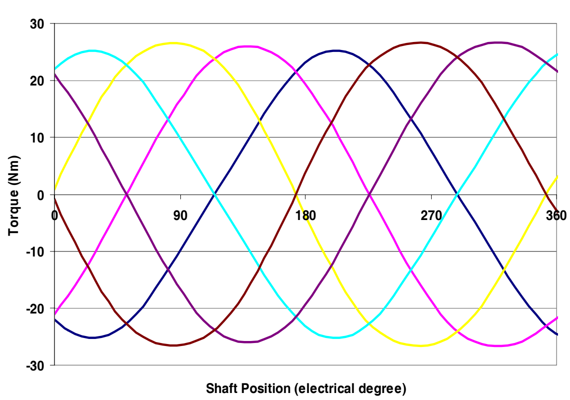

Fig 5. Simulation torque output of axial flux motor

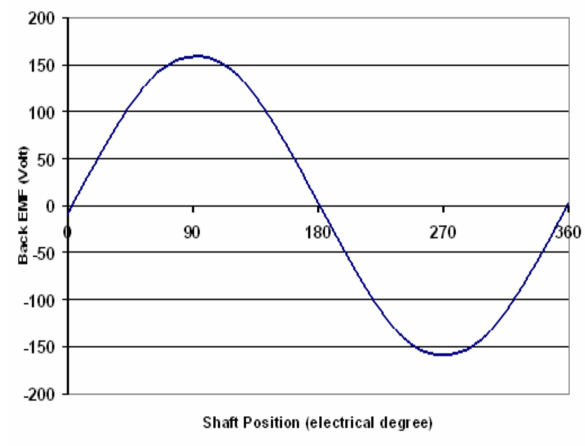

Fig 6. Simulation back EMF

IV. FABRICATION AND EXPERIMENTAL WORK

The axial motor has been fabricated based on the simulated parameters. Several laboratory tests were conducted to investigate its performance at University of Malaya.

A. *Design for Manufacturing*

The challenge of design for manufacturing of the axial flux permanent magnet motor is to maintain the air-gap between stator and rotor. Magnetic interaction between the rotor magnet and the stator back iron is quite large (simulated value for this motor is 752 N). The air-gap needs to be as small as possible. In the design the air-gap is 1 mm. Design assembly of active parts and fabricated of permanent magnet mounted of rotor for the axial flux motor design are shown in Fig. 7 and Fig. 8.

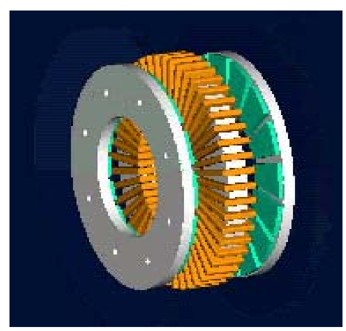

Fig 7. Design of stator and rotor of axial flux permanent magnet motor

Fig 8. Assembly of permanent magnet and Rotor Back Iron of Axial Flux Permanent Magnet Motor

TABLE- II
MOTOR PARTS SPECIFICATIONS

Rotor inner diameter	130mm
Rotor outer diameter	230mm
Number of winding	48
Number of turn	21
Magnetic pole	16
Magnet thickness	7 mm
Magnet arc	18^o
Magnet material	Nd-Fe-B, N35
Back iron thickness	12

B. Experimental Works

The experimental setup is shown in Fig. 9. A National Instrument Data Acquisition System with LabVIEW™ interface is used to obtain the test data and to plot the performance curves. The motor torque and back EMF are the main performance parameters that were obtained in this experiment. During the cruising speed test, secondary measurement such as temperature rise in critical parts of the motor was also recorded. Figure 9 shows the experimental test-bed setup for the motor.

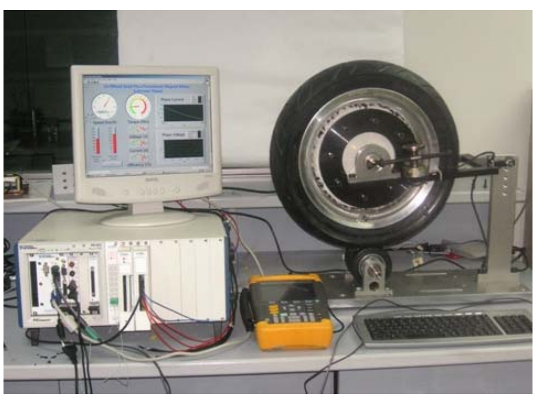

Fig . 9. Experimental Test-bed Setup

Figures 10 and 11 show the graphs of back EMF and torque. The maximum output of the back EMF is 300V peak to peak and the torque output at rated current is about 25 Nm. The back EMF of the motor was acquired by mechanically turning the wheel at a certain speed, and then the terminal voltage was measured. Under such conditions, the machine now acts as a generator. At no load condition, the terminal voltage of the machine is equal to the generated back EMF. The motor torque was measured using a load cell force sensor. The load-cell force sensor is mounted at the free-rolling shaft. Current is injected into the motor from an inverter at a constant controlled value. The wheel was loaded with roller brake. Torque can be increased to maximum value in a short time. Torque can also be increased up to two times the rated value.

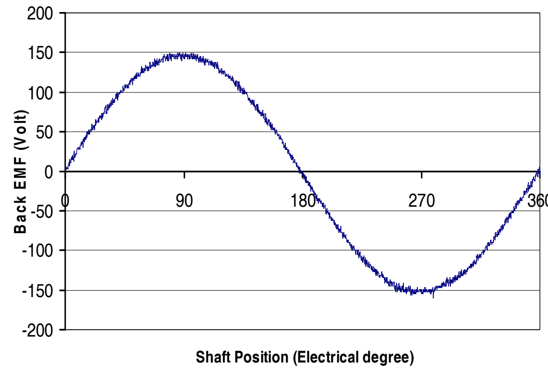

Fig. 10. Experimental Result for the Motor Back EMF

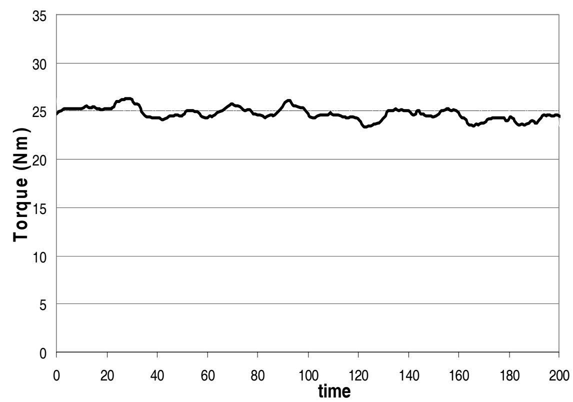

Fig. 11. Experimental Result for the Torque Output

V. DISCUSSIONS

Experimental results have been compared to the simulation results. The actual value of back EMF during testing which is produced by the motor was 301Vp-p at 700rpm. The test result is 4.1% less than the simulated result which is 314Vp-p. The difference between the experimental and simulation results may be due to the slightly different winding arrangements during fabrication as it cannot be done exactly as in simulation due to physical constraints. The torque produced during experiment is 25Nm whereas the simulated torque result is about 26Nm.

VI. CONCLUSION

The design, simulation and testing of the axial flux permanent magnet wheel motor have been presented in this paper. The maximum torque produced by the motor is about 25Nm and back EMF $301V_{p\text{-}p}$ at 700rpm. The design of this motor has achieved the required motor specification and this design is suitable to the EV application. For further investigation, the durability test should be applied to determine the temperature rise and the toughness of the mechanical assembly. The performance of the motor can be increased by optimizing the design with varies parameters such as air gap, permanent magnet and winding dimensions.

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