Design of 3-Phase BLDC Motor for Electric Vehicle Application by Using Finite Element Simulation.

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Abstract—This paper presents the design and simulation of 3-phase double layer coil BLDC motor for Hybrid (HEV) and Electric Vehicles (EV) using ANSYS software. Two 15 kW brushless dc machines (BLDC) which is located inside the rim of the wheels (hub drive system) are designed to produce rated torque and power to drive Electric Vehicles. Two configuration of BLDC motor based on different number of slots and poles combination are simulated and compared for producing optimum rated torque. 2D FE static magnetic analysis is carried out using ANSYS/Emag. Distribution of electromagnetic field in BLDC motor is also analyzed using ANSYS/Emag.

Keywords—BLDC motor, Permanent Magnet (PM), ANSYS Electromagnetic(Emag), Electric Vehicle(EV)

I. INTRODUCTION

Electric cars have several benefits over conventional internal combustion engine automobiles, including a significant reduction of local air pollution, reduced greenhouse gas emissions from the onboard source of power, depending on the fuel and technology used for electricity generation to charge the batteries and less dependence on foreign oil. The governments have started to provide more incentives and, private companies have concentrated on electric vehicle development projects [1]. It is seen that, main attention was focused on series and parallel hybrid drives. Recently however, plug-in hybrids (PHEV) and all electric vehicles (EV) seem receiving more attention. In all front wheel driven types, mechanical differentials are used for rear wheels similar to conventional Internal Combustion Engine (ICE) driven vehicles. Driving each wheel separately by direct drive electric motors without any differential has not been widely adopted. Mainly because of the difficulties of designing an electric machine inside the rim and angular speed limitations governed by vehicle wheels. Only few prototypes have been developed and few studies have been published so far about hub-wheel driven HEVs and EVs [1, 2, and 3].

In hub drive system, rear wheels are replaced by hub electric driven wheels powered by brushless dc motor (BLDC) located inside the rim of the wheels.

Hub drive offers some useful properties. In addition to general advantages of EVs over conventional vehicles like regenerative braking, being silent and pollution free, the hub wheel drive has some additional merits such as; improved maneuver capability, improved road handling, higher stability control, redundancy to ICE, and torque top up capability when vehicle is under HEV modes of operation. This paper presents the design and 2D finite element static magnetic analysis of BLDC motor for a hub drive system using ANSYS/Emag.

II. FINITE ELEMENT METHOD

The finite element formulations used in ANSYS electromagnetic analyses are derived from Maxwell’s equations for electromagnetic fields. 2D Finite Element Method (FEM) begins by dividing the domain area in finite elements (Triangular or quadrilateral). The finite element formulation for 2D static analysis is:

\[
[K]{DU}_{k+1} = \{R\} + \{F\}
\]

\[
{U}\_k = \{U\}_k + \{DU\}
\]

Where: [K] coefficient matrix, \{U\} nodal potential vector, \{DU\}incremental nodal potential vector, \(\{R\}\) applied load vector (current, voltage, or permanent magnets), \{F\} residual load vector, k iteration number.

Two-dimensional magneto static field problems are solved by minimizing a nonlinear magnetic energy functional containing a vector potential (U = Az), resulting in a set of simultaneous equations.

The finite elements method in ANSYS assures sufficient accuracy of electromagnetic field computation and very good flexibility when geometry is modeled and field sources are loaded. This tool includes three stages: preprocessor, solver and postprocessor. The procedure for carrying out a static magnetic analysis consists of following main steps: create the physics environment, build and mesh the model and assign physics attributes to each region within the model, apply boundary conditions and loads (excitation), obtain the solution, and review the results.
III. MATHEMATICAL FORMULATION

Finite Element Method is used to solve electromagnetic field problems using Variational Calculus of Poisson’s type from basic Magneto Static Maxwell equations. The equations relate magnetic vector potential $A$, magnetic flux density $B$ and magnetic field intensity $H$ to obtain the Poisson’s equation. Maxwell’s equations are a set of differential equations used to describe the properties of electric and magnetic fields. The governing equation of the magnetic field is represented by Maxwell’s equation in the form of a magnetic vector potential as

$$\nabla \times H = J + \frac{\partial D}{\partial t}$$

Initially it is assumed no displacement of $D=0$

$$\nabla \times H = J$$

From Gauss Law for magnetism

$$\nabla \cdot B = 0$$

Where, $B$ is magnetic flux density

The quantities $B$ and $H$ can be related as follows

$$B=\mu H$$

Where, $\mu$ is magnetic permeability.

For non-linear materials, the permeability is a function of $B$:

$$\mu = \frac{B}{H(B)}$$

The Magnetic Flux density can also be expressed in terms of magnetic vector potential ($A$) as

$$B=\nabla \times A$$

Where, $A$ is magnetic vector potential [2].

IV. DESIGN SPECIFICATION OF PMBLDC MOTOR

In hub drive system the exterior rotor (ER) configuration is implemented [1]. The motor is embedded into the wheel rim of EV as shown in fig. 2.

A motor designed for EV can be classified as direct drive or indirect drive [6,7]. Direct drive excludes transmission gears and mechanical differential including the associated energy losses. An outer rotor configuration is selected so that it can be coupled directly to the wheel hub. The outer rotor design maximizes the shear force required at the air-gap for a given torque. The motor is mounted inside vehicle wheel rim and turns the wheel directly, so it must be compact and have high torque [8]. The specification of motor drive for electric vehicle is shown in Table 1.

![Fig.2 Direct drive BLDC motor in the wheel rim and motor-generator setup](image)

### TABLE 1

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>1</td>
<td>Rated Power</td>
<td>15 KW</td>
</tr>
<tr>
<td>2</td>
<td>Rated voltage</td>
<td>300 V</td>
</tr>
<tr>
<td>3</td>
<td>Rated Torque</td>
<td>135 Nm</td>
</tr>
<tr>
<td>4</td>
<td>Rotor Type</td>
<td>Outer</td>
</tr>
<tr>
<td>5</td>
<td>Torque constant</td>
<td>2.62 Nm/A</td>
</tr>
<tr>
<td>6</td>
<td>Voltage constant</td>
<td>2.62 Nm/A</td>
</tr>
<tr>
<td>7</td>
<td>No load speed</td>
<td>1320 rpm</td>
</tr>
<tr>
<td>8</td>
<td>Rated speed</td>
<td>1070 rpm</td>
</tr>
<tr>
<td>9</td>
<td>Efficiency</td>
<td>94.3%</td>
</tr>
<tr>
<td>10</td>
<td>No. of Phases</td>
<td>3</td>
</tr>
</tbody>
</table>
V. DESIGN OF BLDC MOTOR

The parameters selected for the design of BLDC motor for above specification of hub drive system in electric vehicle are shown in Table 2.

<table>
<thead>
<tr>
<th>TABLE 2</th>
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<tbody>
<tr>
<td>S.No.</td>
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<tr>
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<tr>
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The motor is designed for 205/55 R 16 wheels, mostly used in vehicles. Thus outer diameter is fixed. The air gap is chosen in such a way that the machine works reliable under common operating conditions in every operating point. NdFeB are used as permanent magnet materials, which is mainly made of Neodymium Iron and Boron, with excellent Energy Product and high Coercive Force.

The choice of the number of poles depends upon many factors, some of which are as follows:
1) Magnet material and grade.
2) Interior-rotor vs. exterior-rotor vs. axial-gap rotor.
3) Mechanical assembly of the rotor and magnets.
4) Speed of rotation.
5) Inertia requirements.

If a rotor is to be designed using embedded slab magnets, there are several possible configurations. All the possible pole-numbers which will operate with stator laminations having slot-numbers from 3 to 48, for 2,3,4,5, and 6 phases has been explored in detail by T.J.E. Miller [10], that have been generated with the aid of a special computer program. Based on this guideline, the stator and rotor pole combinations are taken for 36 number of slots, two configurations are selected, one with 24 number of poles and other with 16 number of poles. Electromagnetic torque is evaluated for both the configuration using Maxwell’s stress tensor approach in ANSYS. 2D static magnetic analysis is carried and the results are compared.

VI. MOTOR DESIGN EQUATION

\[
T = (N_{ph}-1) K_w N_t D L B_g i \\
E = (N_{ph}-1) K_w N_t D L B_g \omega
\]

Where, \(T\)=Torque ,Nm, \(E\)=Emf, \(N_{ph}\) = No. of phases, \(K_w\)=winding factor, \(N_t\)=No.of turns, \(D\)= Diameter of rotor, \(L\)=Length of motor, \(i\)=Current magnitude, \(\omega\)= Rotational speed, \(B_g\)= Magnetic flux density.

VII. ANALYSIS AND SIMULATION OF ERPMBLDC MOTOR USING ANSYS/EMAG

A. Pre-Processing

2D geometric model is generated as shown in fig 3 as per the specified geometric dimension of BLDC motor mentioned in table 2. 8 noded 2D element (PLANE 53) is used to create fine mesh for the region defined by stator, rotor, magnets, coils and air as shown in fig. 4 and corresponding materials properties (permeability and coercitivy) are assigned to the elements.

B. Processing

Flux parallel boundary condition is applied to outer nodes of the rotor. Excitation (current density load) is applied to the coil as per winding layout configuration. Solution is obtained by using ANSYS/Emag solver.
C. Post Processing

The electromagnetic flux distribution and the flux density is plotted and analysed at each elements and nodes as shown in fig 5. Torque on rotor is evaluated using Maxwell stress tensor approach for each incremental rotation of 30 degree and shown in fig. 5.

Simulation of BLDC motor is carried for the two configuration and results are shown below.

VIII. SIMULATION RESULT OF CONFIGURATION I- BLDC MOTOR WITH 36S/24P

BLDC motor with the combination of 36 slots and 24 numbers of poles is simulated and output is shown in fig-5 & 6. Figure 4 shows the model with 2d mesh elements. Figure 5 shows the flux distribution in BLDC motor. When the motor is turned on, i.e. stator coils are excited and the rotor is mechanically rotated, a holding-torque curve is produced as shown in fig 6. In first step phase R is turned off, keeping other phases excited. The holding torque (Nm) curve is plotted by rotating the rotor by varying the angles from $0^\circ$- $360^\circ$ in step of $30^\circ$. Similar curve is obtained for other two phases also and combined graph is shown in Fig-6.

IX. SIMULATION RESULT OF CONFIGURATION II- BLDC MOTOR WITH 36S/16P

Fig-7 shows the model with 2d mesh elements. Fig-8 shows the flux pattern for 16 number of poles. Fig-9 shows absolute magnetic flux density variation in Air gap. A closed circular path is created between air-gap and graph of flux density is plotted on the path. 0.8T flux density is observed as shown in Fig-9.
Holding-torque evaluated by turning off one phase and keeping other phases excited are plotted in Fig-10 to 12. and combined graph is shown in Fig-13.

**X. CONCLUSION**

Finite element simulation of 3 phase BLDC motor for electric vehicle applications is carried out using ANSYS for the two configurations of 36S/24P and 36S/16P. It is observed from the above graphs that the rated torque requirement is achieved from configuration- II (36S/16P). With reduced number of poles high speed of rotation can be easily achieved.

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