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Research Paper

DESIGN AND MODELLING OF BLDC MOTOR FOR AUTOMOTIVE APPLICATIONS

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This paper presents design, simulation and analysis of three phase BLDC motor for automotive applications. Finite Element Analysis (FEA) of the BLDC motor is done to confirm the flux linkage characteristics of the design. The proposed BLDC motor is designed and simulated using FEA based design software tool MotorSolve. Simulation results from the design software tool focuses on the torque and magnetic flux density distribution. The BLDC motor is modelled using MATLAB/ SIMULINK and the dynamic characteristics of PMBLDC motor are monitored.

Keywords: Finite Element Analysis (FEA), BLDC motor, Electronic commutation

INTRODUCTION

The BLDC motor is the most preferred machine for automotive application, as it has high reliability and efficiency. It has the capability to provide large volume of torque for wide speed ranges. Electronic commutation technique and permanent magnet rotor cause BLDC to have immediate advantages over brushed DC motor and induction motor in electric vehicle application [6], [15], [17].

The BLDC motor construction is similar to the ac permanent magnet synchronous motor with permanent magnets on the rotor and windings on the stator [12]. The energized stator windings create electromagnet poles and permanent magnets create the rotor flux. A rotating field is created on the stator and maintained, by using the appropriate sequence to supply the stator phases. The energized stator phase attracts the rotor. This action of rotor chasing after the electromagnet poles on the stator is the fundamental action used in brushless permanent magnet motors. The BLDC motor operates based on the rotor position information. According to the rotor position, the phase windings are switched in a sequence to obtain the rotation [14] [16]. The torque developed in BLDCM is affected by the waveform of back-Emf. Usually the BLDC motor has trapezoidal back-Emf waveform

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and stator is fed by rectangular stator current and theoretically it gives a constant torque but the torque ripple exists due to current ripple, emf waveform imperfection and phase current commutation [13].

Electronic commutation of BLDC Motor control algorithm is more complex compared to other motor types. Therefore accurate model of motor is required to have complete and precise control scheme of BLDC. A motor model providing torque for related values of current and back emf is required to design the drive system [15].

On obtaining the analytical design parameters the electromagnetic analysis is generally done using finite element method which provides solutions based on numerical methods. The method basically involves the discretization of the motor cross-section into smaller areas called finite elements. By using FEM, it is possible to make the accurate field calculations in the electrical machines [7].

ANALYTICAL DESIGN

The analytical designing available in Motor Solve provides an initial design of a motor model. It gives a complete design including dimensions, winding layout, phase coil details and end turn electrical parameters.

In order to determine the size of a radial flux motor that will produce a required torque, the following scaling law can be used [9].

$$T = KD_r^2 L \quad (1)$$

where k is a constant, D_r is the rotor outer diameter and L is the stack length.

where,

$$L = rD_s \quad (2)$$

$$D_s = \frac{D_r}{f} \quad (3)$$

where D_s is the stator outer diameter, r is motor aspect ratio and f is rotor-stator ratio, (1) can be expressed as:

$$T = K\frac{r}{f}D_r^3 \quad (4)$$

Approximate expressions for stator and rotor dimensions can be obtained relating the dimensions of the ferromagnetic portions of the motor to the number of magnet poles, the number of slots and the rotor outside radius

Tooth width, $$w_{tb} = \frac{® D_r B_g}{N_s K_{st} B_t} \quad (5)$$

Back iron Depth, $$w_{sy} = \frac{® D_r B_g}{2N_m K_{st} B_t} \quad (6)$$

Core thickness, $$w_{ry} = \frac{® D_r B_g}{2N_m K_{st} B_{ry}} \quad (7)$$

where, N_s is No. of slots, N_m is No. of poles, K_{st} is Stacking factor. B_t, B_{sy}, B_{ry} are fixed maximum flux density specified in the stator teeth, the back iron depth and rotor core and B_g, Flux density in the air gap.

Power balance between the input power P_i, the mechanical power P_m and the windings losses P_l is expressed as:

$$P_i = P_m + P_l \quad (8)$$

Input power is given by,

$$P_i = N_{ph} V_{rms} I_{rms} \cos ¤ \quad (9)$$

where, $$V_{rms} = \frac{V_{peak}}{\sqrt{2}} = \frac{1}{\sqrt{2}}\frac{V_{line}}{\sqrt{3}} \quad (10)$$

the mechanical power is given by

$$P_m = µT = \frac{2®}{60} V_{rpm} T \quad (11)$$

and the losses (include the Ohmic loss in the coil sides only, the losses in the end turns as well as the core losses are not taken into account) are given by

$$P_l = N_s R_s I^2_{rms} \quad (12)$$

where, $R_s = NN_l \frac{L}{\pm A_\mu}$ (13)

where, N_{ph} is No. of phases, N_s is No. of slots, Irms is Rated current, V_{line} is supply voltage, ± is coil material conductivity, N_l is No. of layers, N is No.of turns and A_w is conductor area [4] and [8].

FINITE ELEMENT ANALYSIS OF BLDC MOTOR USING MOTORSOLVE

Three phase, four pole BLDC is designed using FEA based design software MotorSolve BLDC. Results obtained are analyzed.

Design Of BLDC Motor Using Motorsolve BLDC Software

MotorSolve BLDC is electric motor design software for brushless dc and permanent magnet AC machines which provides easy-to-use templates and an automated-FEA solver to calculate performance. Meeting the growing demand for higher efficiency and lower costs requires software that delivers reliable results and does not give false predictions for crucial performance factors resulting in avoidable and costly complications. Modern electric motors performance cannot be predicted by general approximations and magnetic circuit calculations. In FEA simulations:

- Performance is predictable during saturation.

Table 1: BLDC Motor Specifications

Parameter	Values
Number of phases	3
Number of armature slots	12
Number of poles	4
Outer radius of stator (mm)	45
Inner radius of stator (mm)	25
Outer radius of rotor (mm)	24.5
Inner radius of rotor (mm)	4
Magnet thickness (mm)	5
Magnet gap angle	0
Air gap thickness (mm)	0.5
Stack length (mm)	60

- All sources of loss are accounted such as eddy current and hysteresis.

The geometrical dimensions of the machine are designed using MotorSolve software. The specification of the PMBLDC motor modelled for this project, are given below in Table 1. The computer-aided design is usually the first parts of the electric motor development. The Infolytica MotorSolve is electric motor design software for brushless DC motor. In this motor design is obtained applying different templates. The parameters of the electric motor such as torque, losses, power and the others are calculated by the help of an automated-FEA (Finite Element Analysis) solver. The machine can be designed with the specified parameters like the materials for the construction of stator, the material for the rotor, number of stator slots and number of rotor teeth. From this FEM we can calculate the performance of the motor very accurately and precisely. The output of the designed motor in the FEM contains the output parameters like back EMF, torque characteristics, etc. The disadvantage of the program is that the motor can be designed by using some defined templates only. The easy applicability is the advantage of this program [5] and [9].

The cross section of Brushless DC motor is shown in Figure 1. The simulation results obtained from motorsolve software is shown in following figures. Distribution of flux density within the motor is shown in Figure 2. Torque waveform with oscillation and Back EMF waveform is shown in Figures 3 and 4. Figure 5 shows torque remains constant up to certain speed and then it decreases as speed increases.

Figure 1: Overall Model of BLDC Using Motor Solve

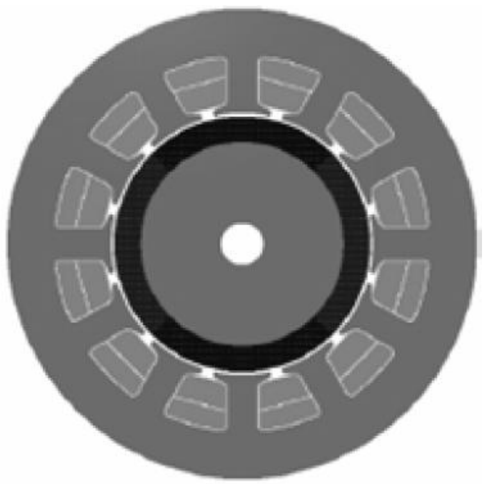


Figure 2: Flux Density Distribution of BLDC Motor

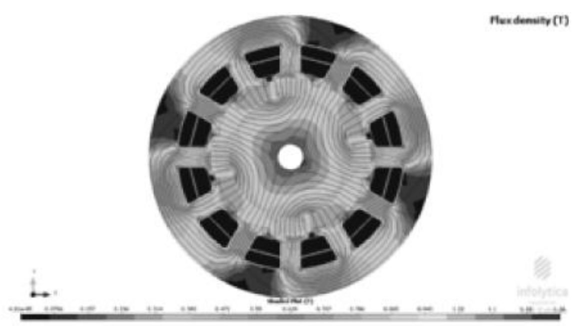


Figure 3: Torque vs Source Phase Angle Waveform

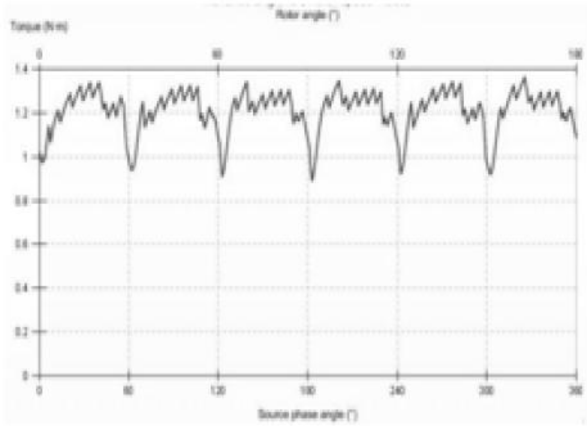


Figure 4: Back EMF Waveform of BLDC Motor

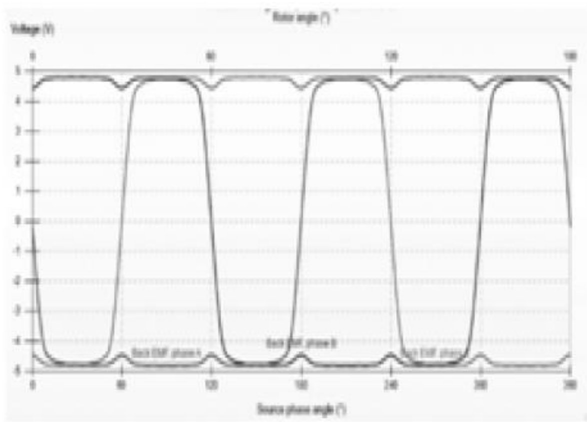
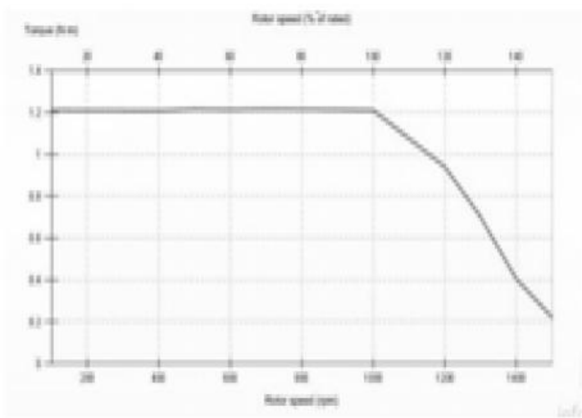


Figure 5: Torque vs Rotor Speed



MATHEMATICAL MODELLING OF BLDC MOTOR

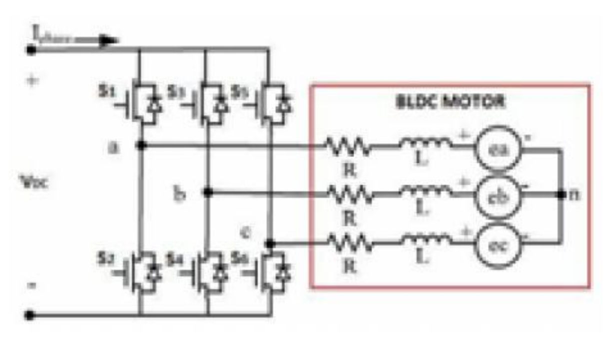
In this paper a 3 phase, 4 pole, star connected trapezoidal back-EMF type BLDC is modelled. The back-emf is trapezoidal due to the trapezoidal mutual inductance between stator and rotor.

Overall model is simplified using following assumptions:

- Saturation in magnetic circuit is ignored.
- All phases have constant and equal stator resistance, self and mutual inductance.
- Losses such as Hysteresis and eddy current are eliminated.
- All semiconductor switches are ideal.

The dynamics of the machine are described by a set of mathematical differential equations. The electrical and mechanical equations can be obtained from the equivalent circuit shown in Figure 6.

Figure 6: Equivalent Circuit of BLDC Motor



The modelled equations for armature winding of BLDC motor are as follows.

$$V_a = Ri_a + (L - M)\frac{di_a}{dt} + e_a \quad (14)$$

$$V_b = Ri_b + (L - M)\frac{di_b}{dt} + e_b \quad (15)$$

$$V_c = Ri_c + (L - M)\frac{di_c}{dt} + e_c \quad (16)$$

where

R : Stator resistance per phase,

L : Stator inductance per phase,

M : Mutual inductance between phases.

i_a, i_b, i_c : Stator current/phase.

V_a, V_b, V_c : The respective phase voltage of winding.

The instantaneous back EMF in BLDC is expressed as:

$$e_a = f_a(^{-})K_e\mu \quad (17)$$

$$e_b = f_b(^{-})K_e\mu \quad (18)$$

$$e_c = f_c(^{-})K_e\mu \quad (19)$$

where, μ is the rotor mechanical speed, K_e is the back EMF constant and ¯ is the rotor electrical position.

The electric torque produced by each phase is the product of the supply current *I* and the motor constant K_t and.

$$T_a = f_a(^{-})K_t i_a \quad (20)$$

$$T_b = f_b(^{-})K_t i_b \quad (21)$$

$$T_c = f_c(^{-})K_t i_c \quad (22)$$

Thus the resultant electromagnetic torque T_e in N-M can be expressed as follows:

$$T_e = T_a + T_b + T_c \quad (23)$$

For simple system ,the equation of motion is,

$$J\frac{d\mu}{dt} + B\mu = T_e - T_l \quad (24)$$

where, T_e is electromagnetic torque, T_l is the load torque, J is motor inertia, B is damping constant [1], [3] and [14].

The PMBLDC motor is modelled in MATLAB/SIMULINK by using above mathematical equations.

Table 2: BLDC Motor Specification

Motor Parameter	Values
voltage	12 V
Rated speed	1000 rpm
Rated torque	1 Nm
Per phase resistance	0.1296 Ω
Per phase inductance	36.12 μH
Back emf constant	4.775*10-2V/radS-1
Torque constant	0.04 Nm/A
No. of poles	4

Simulation Results

The simulation results of modelling of permanent magnet brushless DC motor are obtained by MATLAB/SIMULINK. The motor specifications are given in the Table 2. The back emf waveform for phase A, B and C is shown in Figures 7, 8 and 9 respectively. Trapezoidal back emf is obtained by using the rotor position information. Three back e_a, e_b, e_c displaced from one another by 120°.

Figure 7: Backemf for Phase A

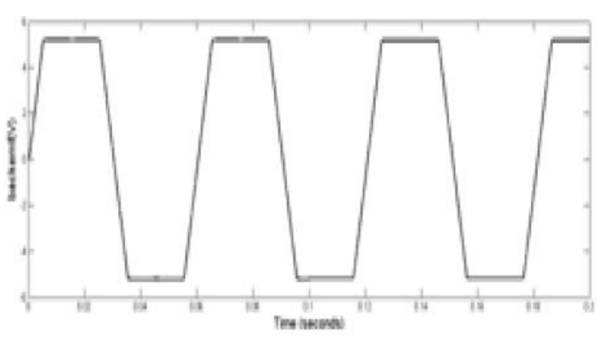


Figure 8: Backemf for Phase B

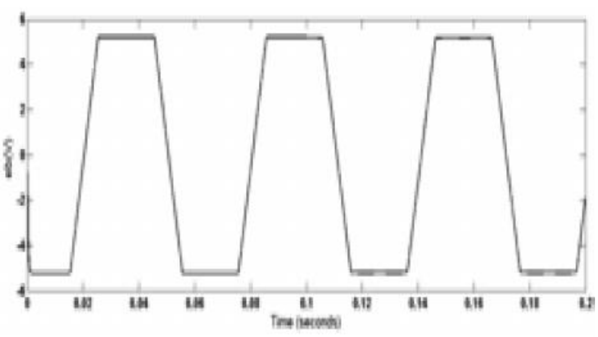
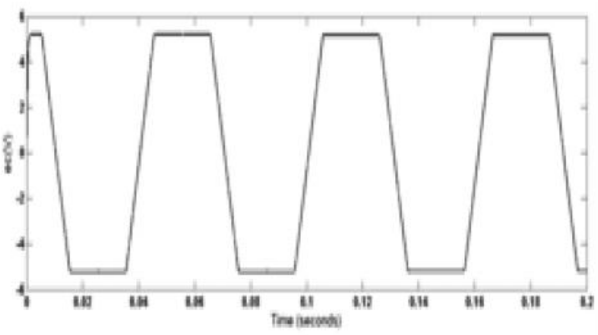


Figure 9: Backemf for Phase C



CONCLUSION

The proposed BLDC motor is designed analytically and analyzed using finite element analysis. The mathematical modeling is done using Matlab to verify the characteristics.

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