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Preliminary communication

Conceptual Design and Material Analysis of BLDC Motor Using FEA Tools for Electric Vehicle Applications

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Abstract: A detailed study was carried out on Permanent Magnet Brushless DC (PMBLDC) motor using Finite Element Method (FEM). The conceptual design of PMBLDC motor is analyzed by selecting various winding and magnetic materials, change in number of turns and altering the chemical compositions of stator material. An analytical approach has been proposed for the research carried out, especially for electrical vehicle applications. The problem and material definitions is given to the electromagnetic field simulation software named Infolytica ©/MagNet 7.1. In field solution, FEM is defined in two dimensional view. The geometrical 2D model, losses and cognitive torque is calculated for 4 pole, 350 W rated power at 1500 rpm speed motor. The analytical results with comparison for existing and proposed system are also presented clearly. The efficiency extracted from the proposed system is 96.4%.

Keywords: brushless motors; cognitive torque reduction; electromagnetic field; finite element method (FEM) analysis; permanent magnet

1 INTRODUCTION

Recently, much of researchers' attention is given to find a new alternative solution to achieve the traction. Nowadays, induction motors are widely used in the electric vehicle. The main drawbacks of using induction motors are the limited efficiency of up to 85%, magnetic losses as well as large size. A quite alternative solution to replace the induction motor is the Brushless DC (BLDC) Motor in the applications in the easily explosive environments such as robotics, aeronautics, chemical and food industries, in the drives field such as adjustable speed and servo drive market. The advantages of the BLDC motor are highly recommendable for clean atmospheric operating conditions, minimal losses with high efficiency and also compactness. The main objective of the proposed system is to prove the BLDC motor is the best solution for the electric vehicle applications by proposing the following material for i) Stator, ii) Winding and its turns and iii) Magnet.

To eliminate the losses and improvement of efficiency of BLDC motor by using Halbach Magnet for drone applications was proposed in [1]. The soft, hard and rare earth magnetic materials are commonly used as permanent magnet in the rotor of BLDC motor. The different ratio of magnetic material combination is a way to improve the efficiency as well as high temperature withstanding capability of the motor. A cogging torque reduction method is proposed for the BLDC motor and was presented in the papers [2]. This method achieved < 2% of peak torque and it also considerably reduced noise and vibration of the motor.

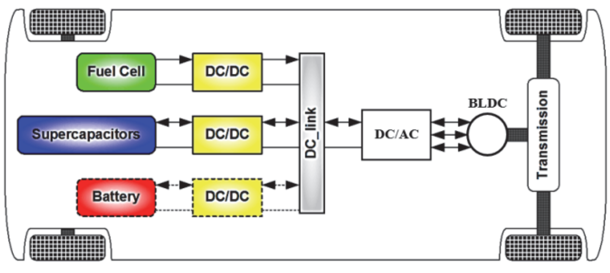


Figure 1 General block diagram of BLDC based electric vehicle

In paper [3] an interior permanent magnet BLDC motor was analysed for electric tools especially car bolts wrench. The bridges, saturation flux and air gap were considered for the analysis purpose. The temperature analysis was also made to verify the magnetic circuit capability. The new wrench design was verified by using Matlab and Finite Element Method (FEM) analysing tools.

The structure and magnetic material analysis for the design of rotor in the BLDC motor was made in [4]. The basic requirement of a drive such as acceleration and deceleration capability and large torque was also applied and better response was obtained. This was undergone in 12/8 poles motor and finally FEA analysis was also presented at the end. The high efficiency and power density BLDC motor was proposed for the application of electric scooter in [5]. The features such as reduction of yoke, coil span and fractional slots per pole are implemented to reduce the size, copper requirements and cogging torque production. This design was analysed by using Pre-flux software. To reduce the cogging torque and increase the efficiency of BLDC motor, Latin sampling and genetic algorithm method were used in the research [6]. The 2D FEM tool was also used to analyze the proposed design model and experimental results proved the results obtained from FEM analysis.

The surface mounted BLDC motor performances were optimized by using Magnet software and optimized design was validated with Particle Swarm Optimization (PSO) algorithm in the paper [7]. The electrical and mechanical parameter of BLDC motor was calculated manually and verified with FEM for the design of 4 pole, 0.75 Hp surface mounted BLDC motor presented in the paper [8]. The design analysis of the motor for the robotics applications was presented in [9]. In paper [10], rotor construction in BLDC motor was altered to reduce the eddy current and iron loss. The significance of the magnet segmentation alteration in rotor reduces the cogging torque and heat dissipation from the machines. The altered 3D model of rotor was verified through Finite Element Analysis (FEA) tool. The iron and eddy current loss are analysed in the low power BLDC motor in the paper [11]. The stator winding methods are commonly used as lap or wave winding. The performance of motor can be improved by using

Quadruplex winding method, and was proven in the thesis [12]. Air gap profile was proposed to improve the starting torque of PMBLDC motor and to reduce the cogging torque using FEA. From this method 70% of starting torque was improved in paper [13]. The permanent magnet machines salient poles are altered to improve the performance of the motor in [14]. The properties of electric circuits, torque such as cogging and starting are analyzed using FEM model in the research [15]. The potentials and limitations of high speed PMBLDC motors are analyzed with structure, diameter and flux density explained in [16].

The potential of high speed BLDC and its limitations was analysed in [17] and numerical analysis of BLDC by using coupled system was proposed in the thesis [18]. The improved iron loss estimation formula was presented in [19]. The determination of pole numbers in stator and rotor core of PMBLDC motor was explained in [20]. From the analysis of the research, iron loss can be minimised by improving stator materials, as proposed and elaborated in the following sections.

The permanent machines stator / rotor diameter ratio was determined in [21]. The magnetic material analysis and slotless BLDC using samarium cobalt magnet was proposed in [22]. From the survey, problem identification of BLDC motor was cleared. The iron loss and cogging torque reduction, improving the efficiency are taken into account for the electric vehicle applications.

The general block diagram of BLDC based electric vehicle is shown in Fig. 1. This paper is organised as follows: The problem identification of the conventional materials used in BLDC motor and the tools required for material analysis are given in sections II and III respectively. Section IV describes the proposed design materials considerations as per material standards and its performance comparison with materials used in the market are analysed in the section V. Finally, conclusions are presented in Section VI.

2 PROBLEM IDENTIFICATION

The problems identified with the using of BLDC motor in electrical vehicles are listed as:

a. Production of cogging torque,
b. Losses,
c. Magnetic materials chosen,
d. Efficiency.

The primary aim of the research is to analysis the mentioned problems root cause and to find the appropriate way to eliminate or mitigate the issues.

2.1 Cogging Torque

The main drawback of BLDC motor is the production of cogging torque and ripples. It is mainly produced in a motor due to the interaction of rotor permanent magnet with the stator tooth. This will lead to vibration and acoustic noise from the motor. The undesirable noises lead to eliminate this motor for the automobile applications. Cogging torque can be expressed as:

$$T_{cog} = -\frac{1}{2} Ø_g^2 \frac{dR_g}{d\theta} \tag{1}$$

where, $Ø_g$ & R_g are the air gap flux and reluctance respectively. To eliminate the cogging torque, stator slots are twisted by making $dR_g/d\theta$ to zero. The twisted stator slots limit the developed torque. So the model can be generated with or without twisted stator slots by using FEM analysis. In this, torque can be mitigated by the proposed stator materials.

2.2 Losses

The losses in the motors are inevitable but they have to be reduced by proper choosing of materials. The main losses such as ohmic, magnetic / iron and copper losses are taken into account for the analysis. In this paper, stator materials are proposed and their composition is less comparatively to others. This leads to reduce the losses.

2.3 Magnetic Materials

The permanent magnetic materials are available as rare earth materials such as Aluminium Nickel Cobalt (Alnico), Samarium Cobalt (Sm Co), Ferrites, Neodymium Boron (Nd Br) and they are mostly preferable to make the rotor for BLDC motor. In order to make the motor compactness, high coercive and permeable materials are the best choice. This can be obtained from Nd Br magnetic materials. The operating magnetic points can be obtained from the following expressions.

The magnetic flux density and airgap are derived by using Gauss's law and it can be expressed as:

$$B_m A_m = B_g A_g \tag{2}$$

$$\frac{B_m}{H_m} = -\mu_o \frac{A_m g}{A_g l_m} \tag{3}$$

$$B_m H_m = \frac{B_g H_g A_g g}{A_m l_m} \tag{4}$$

$$B_m H_m = \frac{2W_g}{V_m} \tag{5}$$

where, B_m & B_g are the magnetic and airgap flux densities, A_m & A_g are the magnet & airgap areas, g is the airgap length, l_m is the thickness of magnet, H_m is the magnetic field density, W_g is the airgap magnetic energy stored and V_m is the magnetic materials volume.

2.3 Efficiency

The efficiency of the motor is the ratio of the output power derived from the motor to the input power given to it. It can be expressed as:

$$\%\eta = \frac{P_{out}}{P_{in}} \times 100 \tag{6}$$

In order to increase the efficiency of the motor, loss reduction is the suitable method.

3 PERMANENT MAGNET BRUSHLESS DC MOTOR

The Permanent Magnet Brushless DC (PMBLDC) motor has the outer stator materials with inner projected salient poles with windings. The rotor has no windings and is made up of 4 poles permanent magnets attached with a shaft which is shown in Fig. 2. It possesses the following criteria such as high torque per ampere, unity power factor, better output to size ratio and high efficiency.

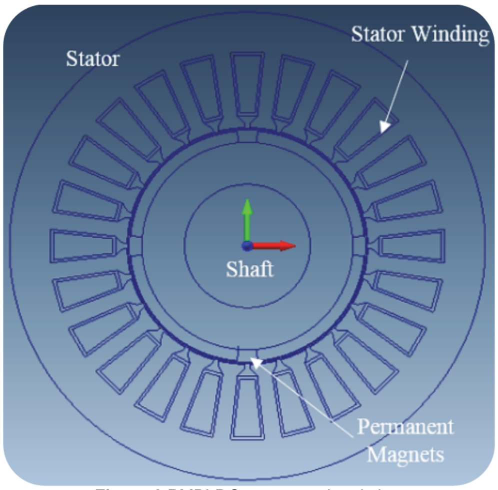


Figure 2 PMBLDC motor sectional view

This motor has no brushes but it performs commutation. The supply is given to stator windings, so heat generated in the stator and easy cool down process prevent the rotor loss. These factors help to maintain high inertia and rotor torque ratio even in small motors. The rotor magnet poles start from two to eight pair combinations with north and south poles alternatively. In typical, Nd-Br magnets are used in the rotor.

3.1 Geometry Model

The geometry model of machines is created using Computer Aided Design (CAD) package used for finite element analysis. The design of surface mounted PMBLDC motor's geometry model is developed in Fig. 3. The parameters to be considered while developing the models are rotor poles either salient or non-salient, magnetic materials, demagnetization in case of overloading.

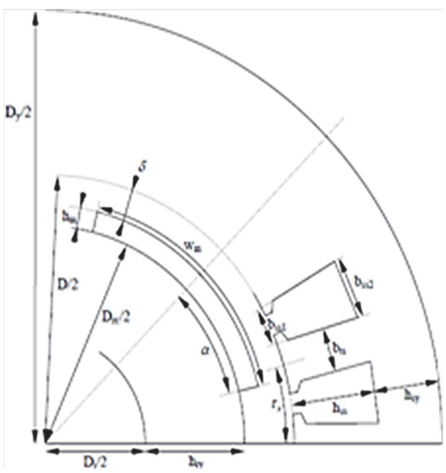


Figure 3 PMBLDC - Geometry model

3.2 Design Criteria

Let,

- Rotor speed, N_s = 1500 rpm
- Torque developed = 60 Nm
- Line-to-Line RMS value of inverter = 35 V
- Length of the motor, L = 0.34 m
- Outer diameter of the stator with bearing, D_y = 0.24 m.

The magnet possesses the following properties such as relative permeability, μ_r is 1.05, demagnetized flux density, BD is –0.2 T and remanence flux density, B_r is 1.1 T. The approximation flux densities are as follows,

✓ Stator Teeth, B_{st} ≈1.8 T,
✓ Stator Yoke, B_{sy} ≈ 1.4 T,
✓ Rotor Yoke, B_{ry} ≈ 1.4 T,
✓ Air gap, B^ ≈ 0.85 – 0.95 T,
✓ Current density = 7 A/Sq.mm.

This criteria are used to solve the insulation issues due to higher thermal temperature occurrence.

4 TOOLS REQUIRED - FINITE ELEMENT METHOD

The required tool for the materials analysis is Finite Element Method (FEM) using the software Infolytica as a version of MagNet software. This is basically numerical as well as analytical approach tool. Compared to analytical approach, numerical analysis method is a quite time consuming process. So, analytical study is carried out in this research. The fundamental issues arising in the electromagnetic field are challenging to solve by numerical approach. They can be overcome by analytical method which is named FEM. This FEM functions based on the computer estimating features related to electromagnetic field, such as electromagnetic torque, flux density & linkages, inductance and back emf will be estimated easily.

The steps involved in FEM are described in the following flow chart as shown in Fig. 4a.

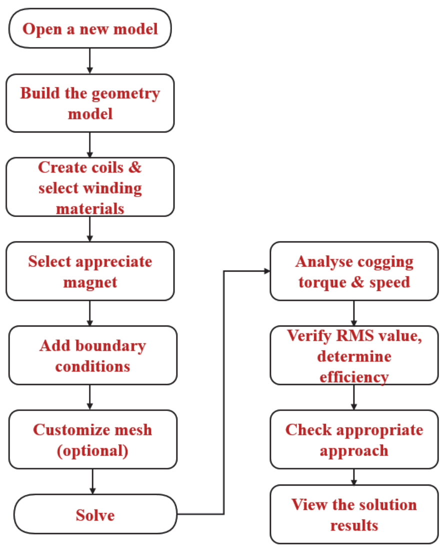


Figure 4a Flowchart - FEM analysis steps involved

The entire approach in FEM is classified into the following three stages. They are:

a. Pre-Processing Stage,
b. Field Solution Stage and
c. Post-Processing Stage.

4.1 Pre-Processing Stage

The pre-processing stage is the initial process stage which is performed in FEM. It consists of i) Mesh generation, ii) Materials definition and iii) Problems definition.

4.1.1 Mesh Generation

The motor volume is divided into a number of segments and it is shown in Fig. 4. This splitting technology helps to understand the problems in the region such as current carrying conductors, stator steel, air gaps as well as magnetic materials. The region contains the elements such as lamination, magnets, core in the rotor and its shaft.

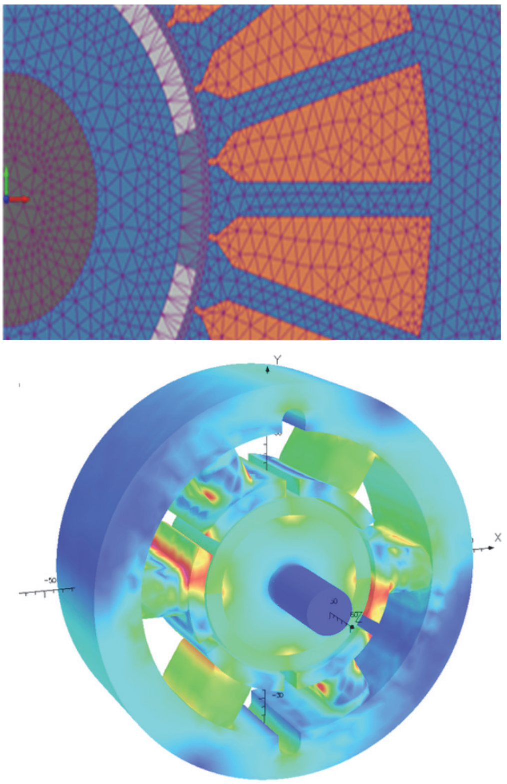


Figure 4b Mesh generation - 2D and 3D model

The benefits of the mesh generation are to create small polygons with symmetrical lines. It deduces the data requirements to specify the geometry of motor and error occurring probability. The modelling of rotation of rotor part along with air gap definitions using a sliding surface. It has to be separated into two layers. One layer is dedicated for rotor and the other is for stator. Initially, spacing between the nodes on sliding surface is kept constant and rotation of rotor can be multiple by this constant. From the analysis of mesh generation of 2D and 3D model of PMBLDC motor, values changes is only 0.005%.

4.1.2 Materials Definition

The magnetic steel has the magnetic flux density, *B* and field intensity, *H* and it relates to a curve called *B-H* curve. It will be useful for the design of motor. The data related to the selected materials are already fed into the FEM program and it gives guidance to user.

4.1.3 Problem Definition

In problem definition, current density must be explained clearly and it will be useful for the selection of winding materials. Similarly, directions and boundary values which are related with magnets for the magnetization also need to be explained clearly. The boundary values can be taken from the periodic basics and will be utilized for designs. In addition, cross section, number of poles and pole pitch are also required to perform the FEM of motor.

4.2 Field Solution Stage

After the pre-processing stage, model is ready for field solution. Then the program will stiffen matrix assembles automatically and solves the potential values. The problem definition in the differential form of equations means mathematical algorithm will be employed.

The main objective is to minimize the energy function. Then the equations are transferred into more number of algebraic form of equations and the process is named as discretization. The algebraic node potential can be found by using Newton Rapson iterations. After this process, flux and current density can be found for every winding element.

4.3 Post Processing Stage

In general, either scalar potential or magnetic vector was used for expressing the field solution. The flux density, electromagnetic torque and electromotive force values must be chosen by the design engineers. These parameters are already existing and their potential solution can be eliminated from the device by certain techniques. This is known as post-processing stage.

5 PROPOSED DESIGN METHOD FOR BLDC MOTOR

5.1 Stator Materials

The stator core materials of BLDC motor used for electrical motors in the market are cold rolled steel and aluminium steel. In this proposed system, the modification can be made in the chemical compositions and a new type steel proposed. It has undergone different analysis and proven its better performance. The materials used for stator are listed as:

i) Cold Rolled Steel,
ii) Aluminium Steel and
iii) Proposed Steel.

5.2 Winding Materials

The winding materials used for the BLDC motors are i) Copper 5.77, ii) Copper 11000 and iii) Copper 12000.

5.3 Number of Winding Turns

The winding material taken for chosen from the analysis is Copper 5.77. The number of winding turns are 38, 46 and 52.

5.4 Magnetic Materials

The Nd-Br with different propositions is used as the magnetic material for permanent magnets in the rotor.

6 PERFORMANCE ANALYSIS AND DISCUSSIONS

The proposed materials for the stator core, winding and rotor magnets performances are analysed and compared with the conventional materials used for BLDC motor in the commercial market. The analyses are presented in the following four cases.

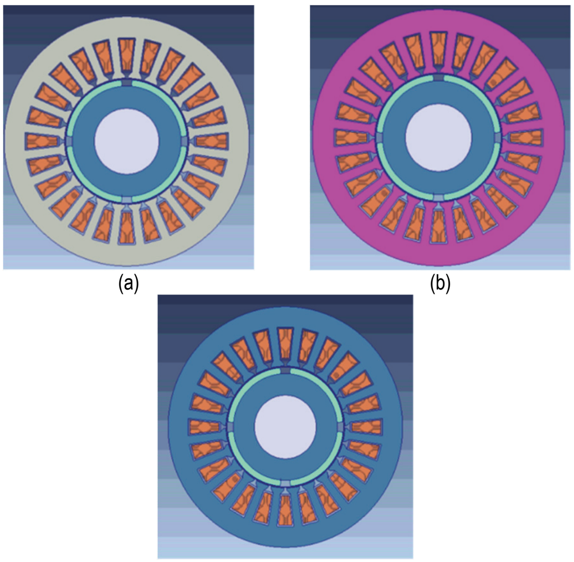
6.1 Case 1 - Stator Materials

The stator materials normally used for the BLDC motor are cold rolled steel and aluminium steel materials. By varying the chemical compositions of the materials, a new combination of steel is proposed for stator core. The chemical compositions of cold rolled steel, aluminium steel and proposed steel are tabulated in the Tab. 1.

Table 1 Chemical Compositions of Stator Core Materials

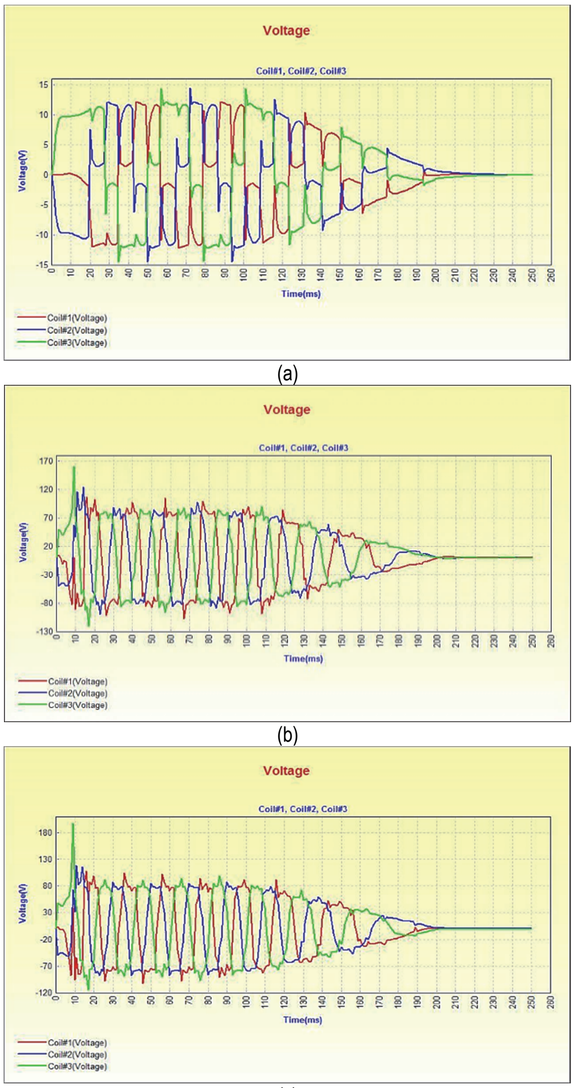
Stator Materials	Chemical Compositions / %				
	Iron	Manganese	Sulphur	Phosphorus	Carbon
Cold Rolled Steel	99.18	0.3	≤ 0.05	≤ 0.04	0.08
Aluminium Steel	Not defined (As per manufacturer)				
Proposed Steel	99.42	0.32	≤ 0.05	≤ 0.04	0.1

The proposed steel material variations are allowed as National Electrical Manufactures Association (NEMA) standards. The three different materials are simulated in the MagNet Infolytica software for the time of 250 seconds. This time is fixed for the obtaining of saturation level. For the analysis purpose, the geometry model obtained, voltage and current waveforms, are presented in Figs. 5, 6, 7 and 8 respectively.



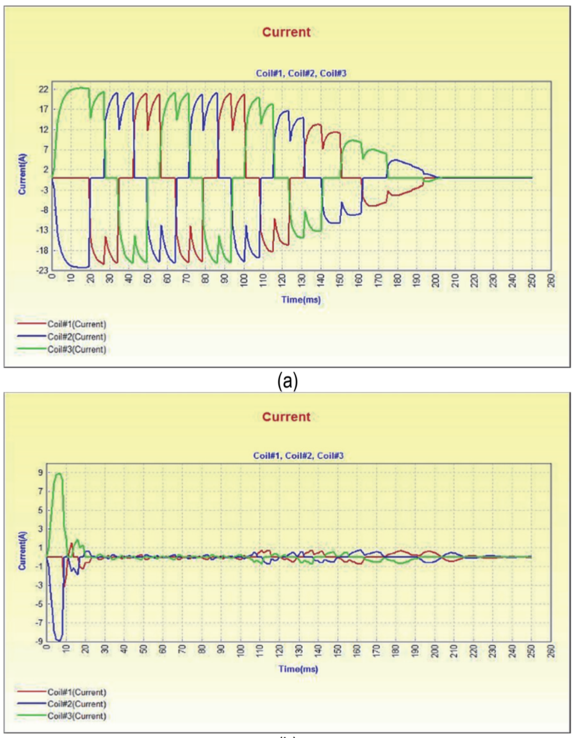
(a) (b) (c)

Figure 5 Models obtained from the simulation
(a) Cold rolled steel; (b) Aluminium steel; (c) Proposed steel

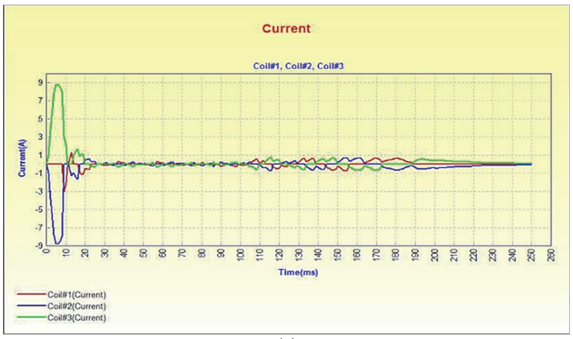


(a) (b) (c)

Figure 6 Voltage waveforms obtained from the simulation
(a) Cold rolled steel; (b) Aluminium steel; (c) Proposed steel



(a) (b)

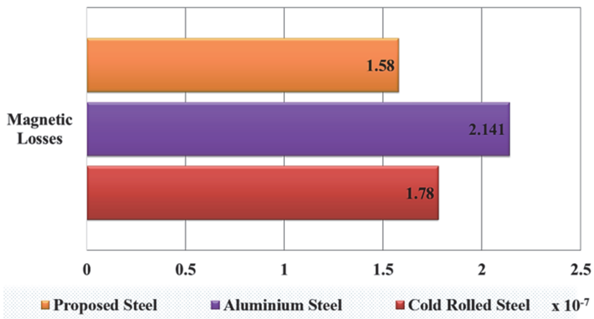


(c)

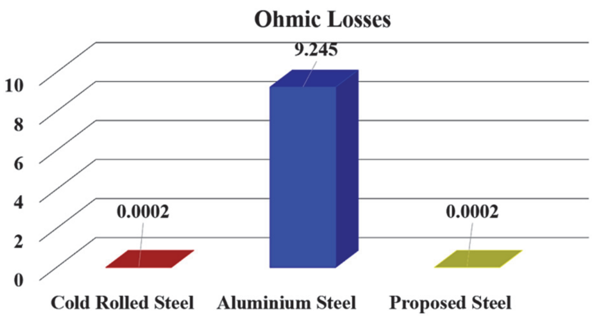
Figure 7 Current waveforms obtained from the simulation
(a) Cold rolled steel; (b) Aluminium steel; (c) Proposed steel

The major problem is identified earlier as cognitive/cogging torque and losses in the motor. The PMBLDC motor model is obtained at the position of 1361.9 deg, rotor speed is 29.98 deg/s and its acceleration rate is 1302.19 deg/s^2.

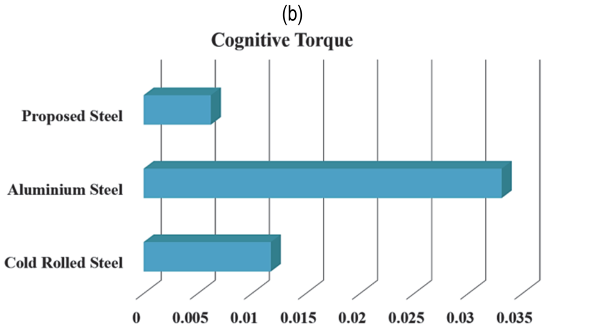
From the voltage and current waveforms obtained from the simulation, proposed material shows the distortion level is the same as aluminium steel and the settling time is less when compared to others. In order to prove the proposed material composition reduces the cogging torque and magnetic loss, its values are plotted in Fig. 8.



(a)



(b)



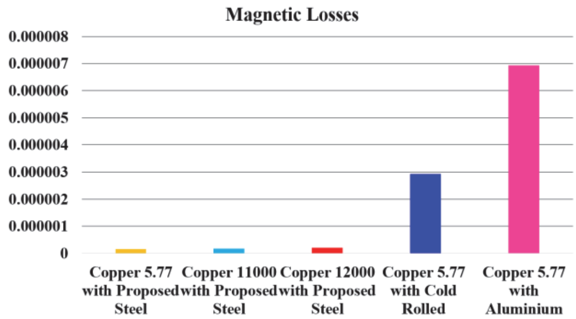
(c)

Figure 8 Analysis of proposed steel materials for stator
(a) Magnetic losses; (b) Ohmic losses; (c) Cognitive torque

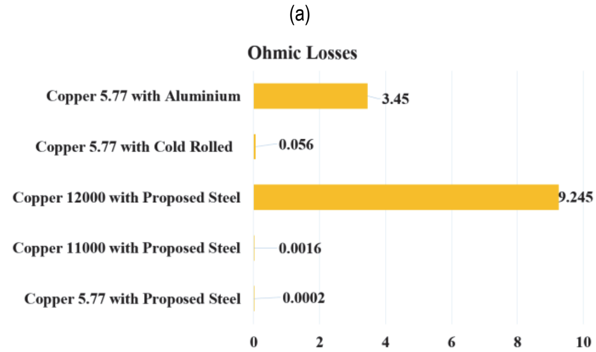
The performance of the proposed steel stator materials is in the order of cold rolled, aluminium and proposed steel respectively. The magnetic losses obtained from the cold rolled steel are 1.78×10^{-7} W, aluminium steel 2.141×10^{-7} W, proposed steel 1.58×10^{-7} W. The ohmic losses obtained from the cold rolled steel are 9.245 W, aluminium steel 0.0002 W, proposed steel 0.0002 W. It shows that losses can be minimised from the proposed materials. The undesired cognitive torque obtained from the cold rolled steel is 0.012 Nm, aluminium steel is 0.033 Nm, proposed steel is 0.006 Nm. The cognitive torque reduced 50% and 80% from the cold rolled and aluminium steel materials.

6.2 Case 2 - Winding Materials

The winding materials are chosen based on the conductivity nature. The best conductive material in the descending order is silver, copper, gold and aluminium. Among this, silver is not abundantly available in earth surface and gold is highly expensive.



(a)



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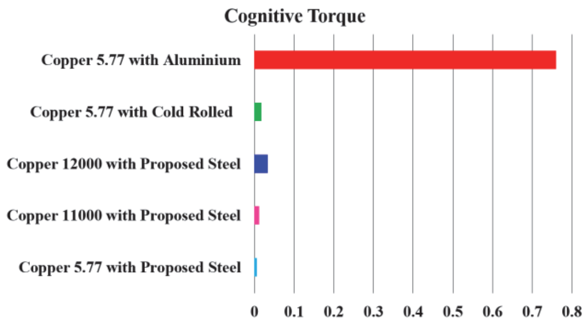

(c)

Figure 9 Analysis of winding material with proposed and existing steel
(a) Magnetic losses; (b) Ohmic losses; (c) Cognitive torque

The aluminium conduction is 50% less than the copper materials. So, copper material is generally used for motor winding. It depends on the composition and as used for electric vehicle is classified into copper 5.77, 11000 and

12000. These copper materials are commonly used in the market. The proposed steel materials are analysed with the three different combinations of winding materials and also with the existing stator materials.

The performance of the proposed steel and existing stator materials with copper 5.77, 11000 and 12000 is analysed. The magnetic losses obtained are high in the combination of copper 5.77 with aluminium steel and low in copper 5.77 with proposed steel. The ohmic losses and cognitive torque is extremely low in copper 5.77 with proposed steel. From the analysis, Cu 5.77 with proposed steel performance is quiet attractive compared to others.

6.3 Case 3 - Magnetic Materials

The magnetic materials Neodymium Boron (Nd-Br) with different proportions are taken into account for analysis with proposed and existing stator steel materials.

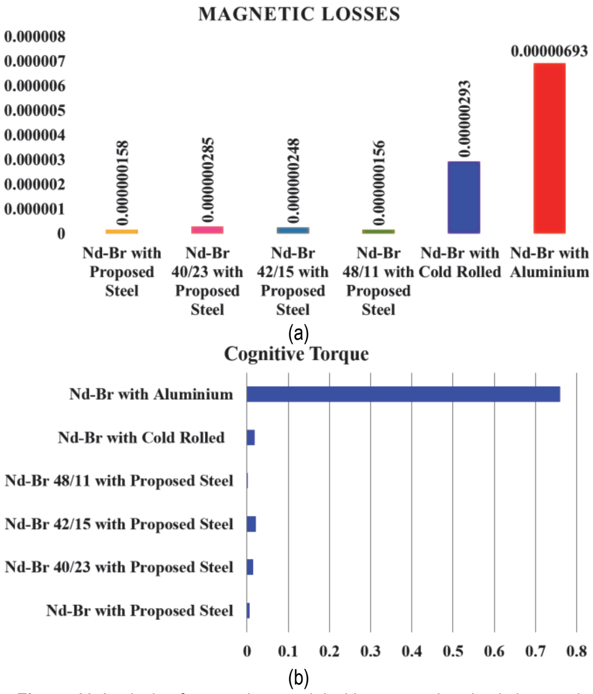

Figure 10 Analysis of magnetic material with proposed and existing steel (a) Magnetic losses, (b) Cognitive torque

The cognitive torque of the magnet Nd-Br 48/11 for the proposed material is less compared to other materials. The ohmic losses are equal for all materials. The magnetic losses of the magnet Nd-Br 48/11 for the proposed material is less compared to other materials. Finally it can be concluded that the Magnet Nd-Br 48/11 could be used for Proposed PMBLDC Motor for better efficiency, as the losses are less.

6.4 Case 4 - Number of Turns per Phase Coil

The coil turns are directly proportional to the current carrying capacity. The analysis is taken for three different turns such as 38, 46 and 52 turns. When the turns increase, magnetic losses decrease and it is shown in Fig. 11a.

The ohmic losses have unexpectedly shown their results. The losses at 38 turns per coil are 0.0008 W, 1.662 W at 46 turns and 0.0002 W at 52 turns per coil. The cognitive torque production is also less when the number of turns is 52.

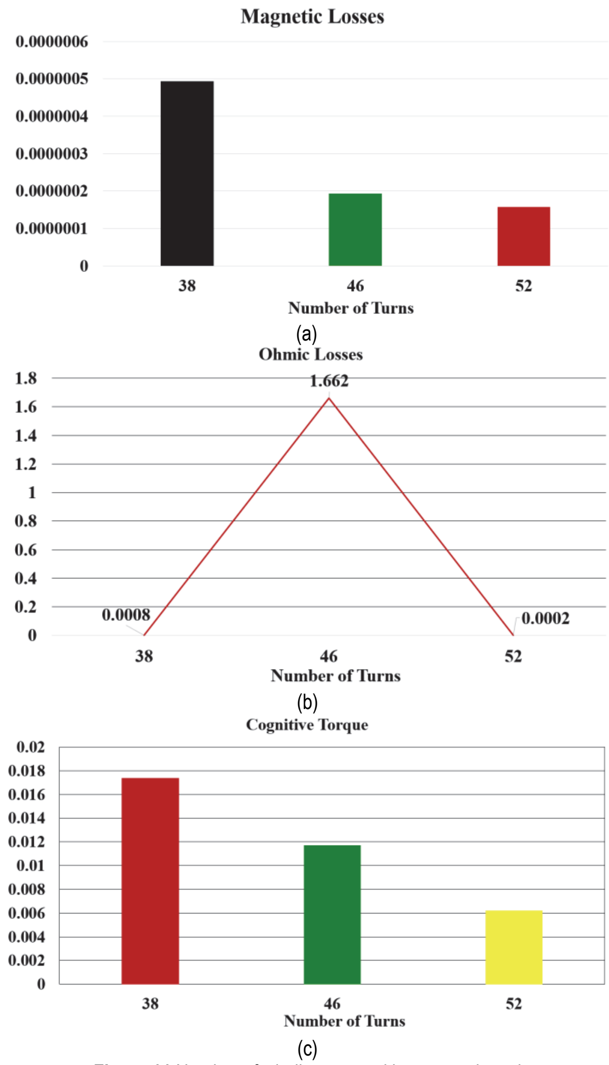

Figure 11 Number of winding turns with proposed steel (a) Magnetic losses; (b) Ohmic losses; (c) Cognitive torque

6.5 Efficiency Analysis of the Proposed System

The Root Mean Square (RMS) current value of the BLDC motor is the ratio of the back emf to the resistance per phase. It can be expressed as:

$$I_{\mathrm{RMS}} = \frac{E}{R} \tag{7}$$

where: E - back EMF at rated speed, R - resistance per phase.

The input power is the product of input voltage and rms current to the motor. The output power is the product of torque and speed obtained from the motor.

From Eq. (6), efficiency can be calculated as:

$$\%\eta = \frac{P_{\mathrm{out}}}{P_{\mathrm{in}}} \times 100$$

$$\%\eta = \frac{Torque \times Speed}{Input\,voltage \times RMS\,current} \times 100$$

$$\%\eta = \frac{1.7\times 129}{155\times 1.467}\times 100$$

$$\eta = 96.43\%.$$

Table 2 Design specifications of BLDC motor

Parameters	Values
Number of stator poles	6
Number of rotor poles	4
Input voltage	155 V
Input RMS current	1.467 A
Rated Torque	1.7 Nm
Rotor speed	129 rad/s
Rated speed	1500 rpm
Motor type	Surface mounted
Efficiency	96.4%

7 CONCLUSIONS

In this paper, PMBLDC motor of 4 pole 350 Watts, 155 V for 1500 rpm is designed for electric vehicle applications using FEM tools. To evaluate the proposed system, comparison of different winding materials, stator materials and number of turns in the coil is analysed. The minimized cognitive torque, losses and improved overall efficiency by using the proposed stator steel, copper 5.77 winding with 52 turns and magnetic material as Nd-Br 48/11 have proven better performance than the other materials available in the market. The results illustrated that proposed BLDC motor achieved 96.4% efficiency even the maximum efficiency of induction motor reached up to 85%. It is suggested the altering of materials also reduces the losses with modifying constructional features.

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