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Efficiency Improvement of Radial Flux Permanent Magnet Brushless DC Motor Using Hiperco Magnetic Material

Tejas H. Panchal[#1], Rajesh M. Patel[*2], Amit N. Patel[#3]

[#1, #3]*Department of Electrical Engineering, Institute of Technology, Nirma University, Ahmedabad, India*
[*2]*Department of Electrical Engineering, MEFGI's Faculty of PG Studies, Rajkot, India*

[1]tejas.panchal@nirmauni.ac.in, [2]r_mpatel77@hotmail.com, [3]amit.patel@nirmauni.ac.in

Abstract — *Performance enhancement of permanent magnet brushless dc motor during design is highly desirable. With the application of superior magnetic material Hiperco in place of traditional magnetic material M19 silicon steel, the performance of the permanent magnet brushless dc motor (PMBLDC) can be greatly improved. Compared to standard silicon steel material the Hiperco magnetic material has high allowable flux density, high permeability and low specific iron loss. This paper presents the use of Hiperco magnetic material for the stator core of PMBLDC motor. The 200 W, 24 V radial flux PMBLDC motor is designed analytically and modelled in finite element analysis (FEA) software. The initial design incorporates use of M19 – 29 Ga Cold Rolled Non Oriented (CRNO) silicon steel material for the stator core. The initial design is validated using finite element analysis. In improved design, the conventional stator core material is replaced by Hiperco magnetic material and effect of Hiperco on the efficiency of the PMBLDC motor is analyzed. The improved model with the application of Hiperco is analyzed with FEA technique. It is analyzed that efficiency of PMBLDC motor is considerably improved with application of Hiperco.*

Keywords — *Brushless dc motor, Efficiency, Finite element analysis, Hiperco material.*

I. INTRODUCTION

Electrical motors approximately consume 70 % of the total energy generated worldwide. Electrical motors' efficiency and energy management has generated immense concern. Even 1 % improvement in efficiency of electrical motors will save immense quantum of electricity units per year. Requirements of electrical motors operating at high efficiency is the need of hour. PMBLDC motors offer high efficiency, compactness, high torque/weight ratio and have been widely used for electric vehicles and domestic electrical appliances [1]-[3]. Permanent magnet motors are emerging as replacement of induction motors in small rating applications specifically. Efficiency of electrical motors is highly influenced by magnetic material used for the core. Main features of magnetic materials are magnetic permeability and specific iron loss. A good magnetic material possess high magnetic permeability and low specific iron loss. Selection of core material plays vital role to enhance performance of motor. To improve the motor's efficiency, proper electrical steel material has to be used as laminating material. Iron loss is one of the vital constituents of various losses in electrical motor. The efficiency of a PMBLDC motor can be increased by reducing its iron losses. The iron loss of PMBLDC motor can be reduced with usage of improved core material of low specific iron loss (W/kg).

H. Toda, et al. have shown that use of newly developed non-oriented electrical steel sheet material (JNP Core) for laminated core improves efficiency of PMBLDC motors [4]. These materials offers high flux density and relatively low iron loss. R. Kolano et al. developed production technology of amorphous soft magnetic materials (ASMMs) used to build stator cores of high speed PMBLDC motors [5]. They demonstrated that the replacement of FeSi steel based stator core with ASMMs in high speed PMBLDC motor resulted in substantial reduction in stator iron losses. Hence, the operating efficiency of PMBLDC motor is increased. W. Chen et al. have shown that in multipolar PMBLDC motor, stator core made from ferrite provides higher efficiency than that made from silicon steel material [6]. It is because of lower iron losses of ferrite core in high frequency drives. T. Ishikawa et al. analyzed a brushless dc motor, the stator and rotor core of which are made of soft magnetic composite (SMC) material. [7]. SMC material has low eddy current loss, reduced production cost and good recyclability. It is analyzed that when rotating at high speed, motor efficiency made from SMC core is higher than core made of standard steel laminations. This paper presents efficiency improvement of PMBLDC motor with usage of Hiperco magnetic material for the stator core. In initial design, M19-29 Ga silicon steel material is used for stator core of PMBLDC motor. The stator iron loss and efficiency are calculated by analytical method. The analytical design is validated using FEA. As Hiperco material sustains high flux density, the design is modified by assuming high flux density in stator teeth and the core. The improved design is obtained by replacing M19-29 Ga silicon steel material of stator core and teeth with Hiperco. The stator iron loss and efficiency are calculated analytically and the improved design is validated using FEA. Section II presents properties of Hiperco magnetic material. Section III describes the initial design of radial flux BLDC motor and FEA. Section IV is devoted to improved design of radial flux PMBLDC motor with application of Hiperco magnetic material and FEA. The simulation results are also presented and discussed in this section. Comparative analysis and concluding remarks are presented in Section V.

II. PROPERTIES OF HIPERCO MAGNETIC MATERIAL

The efficiency of radial flux PMBLDC motor can be increased by reducing stator iron losses. Iron losses can be decreased considerably by using magnetic materials having superior properties like low specific iron loss, high permeability and high permissible flux density. Hiperco is a soft magnetic alloy of iron-cobalt-vanadium that has high magnetic saturation (24 kilogauss), high permeability, low coercive force and low specific iron loss. It is used for making rotor and stator laminations in motors and generators for aircraft power generation applications where high magnetic saturation is required with compactness and less weight. The B-H curves of M19-29 Ga core material and Hiperco are shown in Fig. 1 respectively. It is visualized that Hiperco magnetic material has knee point of magnetization at higher flux density compared to M19 core material. Hiperco is suitable for flux density of 2.4 T while M19 core material is suitable for flux density of 1.8 T.

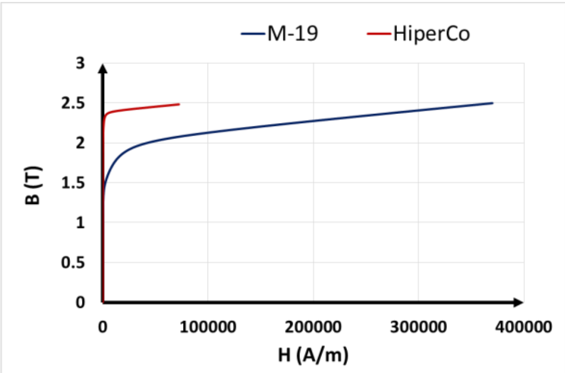

Fig. 1: B-H curve of M19 and Hiperco material

Hiperco has lower specific iron loss compared to M19 core material. The comparison between specific iron loss of Hiperco and M19 core at 33.3 Hz frequency is shown in Fig. 2. It is clearly visible from the curve that at 1.5 T and 33.3 Hz frequency, Hiperco magnetic material has specific iron loss of 0.5 W/kg while M19 core material has specific iron loss of 1.2 W/kg. Thus, Hiperco magnetic material has relatively good properties than M19 core material. Following are some of the properties of Hiperco magnetic material:

- Saturation Induction: 24,000 Gausses
- Maximum permeability: 12,000
- Coercive force: 72 A/m
- Curie temperature: 938 °C
- Melting point: 1427 °C
- Electrical resistivity: 41 μΩ-cm

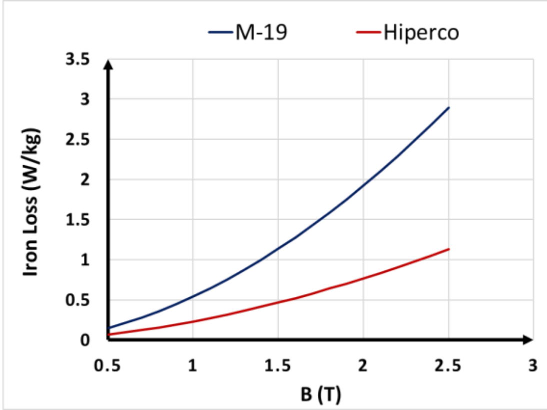

Fig. 2: Specific iron loss curve of Hiperco and M19 core material

III. REFERENCE DESIGN OF RADIAL FLUX BLDC MOTOR

The 200 W, 24 V, radial flux BLDC motor is initially designed and is considered as reference motor for the analysis. The reference radial flux BLDC motor is designed by assuming various design variables like airgap flux density of 0.6 T, stator core flux density of 1.5 T, stator teeth flux density of 1.8 T, current density of 5 A/mm^2, space factor of 0.3, winding factor of 0.95 and stacking factor of 0.95. The details of design of reference PMBLDC motor is illustrated in Table 1.

Table 1: Design output of initially designed 200 W PMBLDC motor

Sr. No.	Parameters	Value
1.	Stator outer dia.(mm)	87
2.	Stator inner dia.(mm)	52
3.	Axial length (mm)	50
4.	Thickness of magnet(mm)	5
5.	No. of phases	3
6.	No. of stator slots	24
7.	Pole numbers	4
8.	Material of stator core	M19-29 Ga
9.	PM material	NdFeB
10.	Copper loss(W)	30.94
11.	Iron loss(W)	1.95
12.	Friction loss(W)	2
13.	Total loss(W)	34.89
14.	Efficiency (%)	85.14

M19 – 29 Ga silicon steel material is used for stator core in reference design. It is analyzed that an efficiency of 85.14 % is obtained using M19 as stator core material.

The validation of design is carried out by conducting FE analysis using FEA software. The cross section of FE model of 200 W radial flux brushless DC motor is shown in Fig. 3.

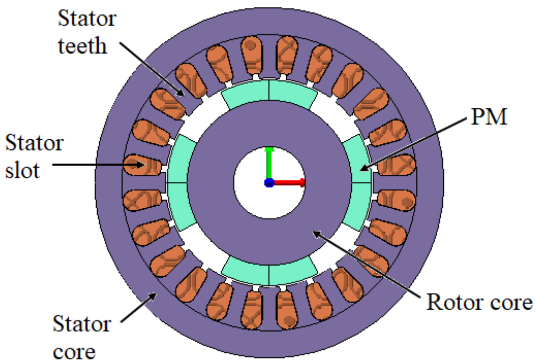

Fig. 3: Cross sectional view of initial model of 200 W motor

Electromagnetic field analysis is quite important as it establishes validation of analytically designed motor. The actual flux density in different sections of the motor should match with the assumed flux densities. Electromagnetic field analysis is accomplished by conducting FE analysis using FEA software. The FEA software uses vector magnetic potential and Maxwell's equations to calculate flux density and field intensity in various parts of PMBLDC motor. The field plot of the reference design is shown in Fig. 4. The flux density obtained in different sections of the motor is fairly matching with the assumed flux densities of analytical design. Hence, the design is validated.

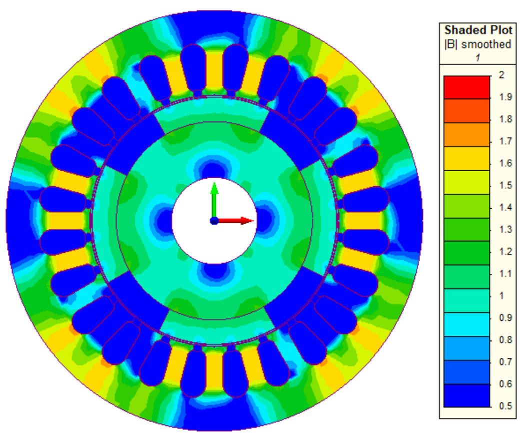

Fig. 4: Field plot of initially designed 200 W motor

The average torque produced by the motor has been determined with two dimensional FE analysis. 2-D transient simulation and analysis has been carried out. In this analysis, the rotor is treated as motion component and the stator winding is energized by appropriate switching of inverter switches. The value of electromagnetic torque at discrete rotor positions are obtained and plotted against these rotor positions. Fig. 5 shows torque profile of reference motor. The average torque obtained using FE analysis is 1.91 N.m. Torque obtained with FE analysis is fairly matching with the target value of 1.90 N.m.

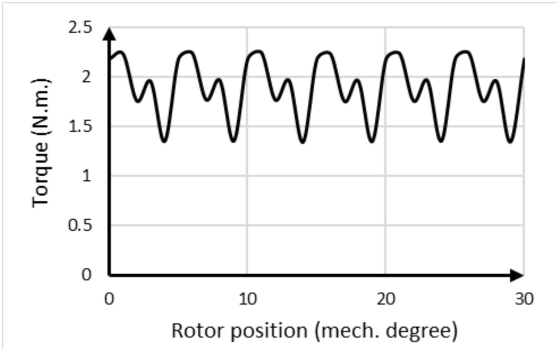

Fig. 5: Average torque profile of reference design of BLDC motor

IV. IMPROVED DESIGN WITH APPLICATION OF HIPERCO MATERIAL

Usage of Hiperco magnetic material for the stator core and teeth improves the initial design of BLDC motor. The motor is designed by assuming various design variables like airgap flux density of 0.8 T, stator core and teeth flux densities of 2.2 T, winding factor of 0.95 and stacking factor of 0.95. Higher flux density is assumed in stator core and teeths as Hiperco has superior magnetic properties. Table 2 shows design information of improved motor.

Table 2: Design output of improved model of 200 W PMBLDC motor

Sr. No.	Parameters	Value
1.	Stator outer dia.(mm)	80
2.	Stator inner dia.(mm)	52
3.	Axial length (mm)	50
4.	Thickness of magnet (mm)	5
5.	No. of phases	3
6.	No. of stator slots	24
7.	Pole numbers	4
8.	Material of stator core	Hiperco
9.	PM material	NdFeB
10.	Copper loss(W)	27.1
11.	Iron loss(W)	0.93
12.	Friction loss(W)	2
13.	Total loss(W)	33.87
14.	Efficiency (%)	86.80

The Hiperco has low specific iron loss as shown in Fig. 2. Hence, iron loss in stator core can be reduced considerably if Hiperco is used for the stator core. Iron loss is reduced from 1.95 W in initial design to 0.93 W in improved design. The iron loss, copper loss and efficiency are calculated using analytical method. It is observed that the efficiency is increased to 86.80 % using Hiperco as stator core material compared to 85.14 % when M19 core material is used as stator core material. The validation of design for the improved motor is carried out by conducting FE analysis using FEA software. The cross section view of improved design is shown in Fig. 6.

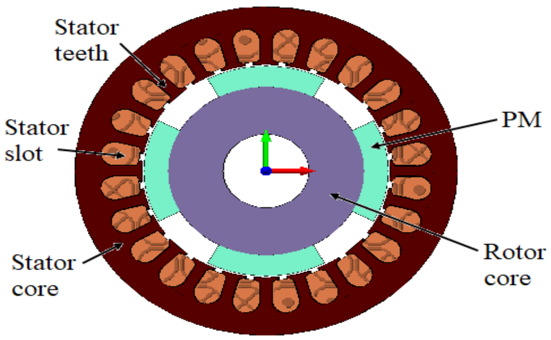

Fig. 6: Cross sectional view of improved model of 200 W motor

Electromagnetic field analysis for improved design is carried out by conducting FE analysis using FEA software. The field plot of improved design is shown in Fig. 7. The actual flux density obtained in different sections of motor is fairly matching with the assumed flux densities of analytical design. Hence, the design is validated. As shown in Fig. 1, knee point of magnetization is 2.3 T for Hiperco magnetic material. Therefore, higher flux densities of 2.2 T is obtained in stator core and stator teeths without causing saturations in stator stamping.

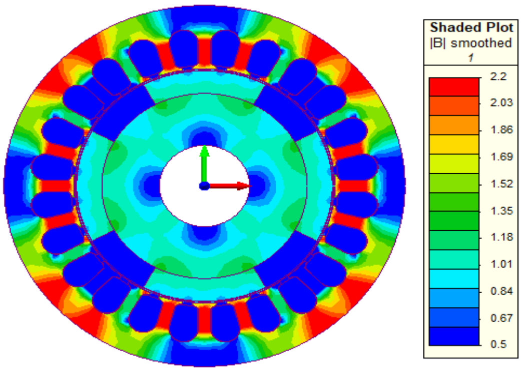

Fig. 7: Field plot of improved design of 200 W motor

Comparison between average torque of reference design and improved designs with application of Hiperco magnetic material is shown in Fig. 8. It is observed that initial design has average torque of 1.91 N.m. The average torque obtained with application of Hiperco magnetic material is 1.92 N.m. against target torque of 1.90 N.m.

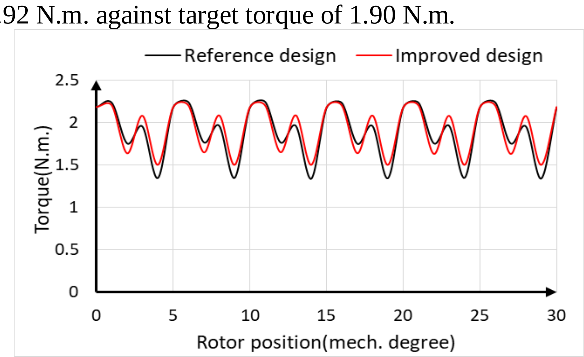

Fig. 8: Comparision between average torque profile of reference design and improved design

The back emf profiles of reference design and improved design are shown in Fig. 9. It is observed that dips in flat top of back emf waveform is slightly reduced in improved design compared to initial design.

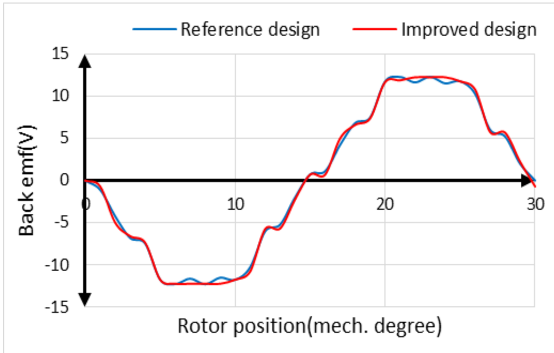

Fig. 9: Comparision between back emf waveform of reference design and improved design

The performance parameters of initial design and improved design are compared and tabulated in Table 3. As magnetic saturation and permeability of Hiperco is high it enables the designer to assume flux density upto 2.2 T in the stator core material. The application of Hiperco material reduces the volume and weight of the motor. The total weight of the motor reduces from 2.169 kg to 1.84 kg with the application of Hiperco material. The motor becomes lighter in weight and compact in size using Hiperco material. The torque density increases from $6.42x10^3$ N/m^2 to $7.6x10^3$ N/m^2. The power density also increases from $6.7x10^5$ W/m^3 to $7.96x10^5$ W/m^3. The efficiency of initial designed motor obtained from FE analysis is 85.6 % which is fairly matching with the efficiency obtained from analytical method. The efficiency of improved design obtained from FE analysis is 86.8 % which is in line with that of analytical method. Use of Hiperco material for stator core increases the efficiency of motor by nearly 2 %.

Table 3: Comparison between performance parameters of initial and improved design using FEA

Performance Parameters	Core material: M19	Core material: Hiperco
Efficiency	85.6 %	86.8 %
Total weight	2.169 kg	1.84 kg
Power density	6.7×10^5 W/m^3	7.96×10^5 W/m^3
Torque density	6.42×10^3 N/m^2	7.6×10^3 N/m^2
Stator outer diameter	87 mm	80 mm
Tooth width	3.5 mm	2.6 mm
Depth of slot	10.8 mm	8.85 mm
Area of slot	40 mm^2	40 mm^2
Depth of stator back iron	6.7 mm	4.9 mm
Magnet	5 mm	5 mm

thickness		
Volume of stator core	1.385 x10^{-4} m^3	9.174 x10^{-5} m^3
Weight of stator core	1.06 kg	0.745 kg
Volume of rotor core	5.33 x10^{-5} m^3	5.33 x10^{-5} m^3
Weight of rotor core	0.408 kg	0.408 kg
Volume of PM	2.209 x10^{-5} m^3	2.209 x10^{-5} m^3
Weight of PM	0.169 kg	0.169 kg
Weight of stator	1.592 kg	1.263 kg
Weight of rotor	0.577 kg	0.577 kg
Axial length	50 m	50 m
Copper loss	27.3 W	26.5 W
Core loss	1.92 W	0.91 W
Windage & friction loss	2 W	2 W
Total loss	31.22 W	29.41 W

Fig. 10 shows per unit relative performance parameters of reference design with M19 as stator core material and improved design with Hiperco as stator core material. It is analyzed that application of Hiperco material significantly reduces core loss and increases efficiency of radial flux BLDC motor. The total weight of the motor with application of Hiperco material reduces. The power density, power to weight ratio and torque density of the motor increases significantly with application of Hiperco material. Thus, the motor becomes compact in size having more power and torque densities when Hiperco material is used for stator core. The average torque of the motor remains nearly equal to the targeted value of 1.90 N.m.

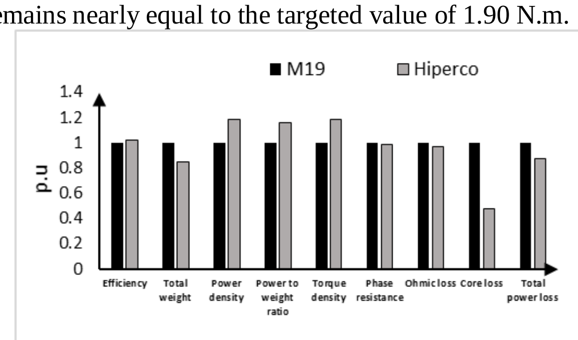

Fig. 10: Comparison between per unit performance parameters of reference design and improved design

V. CONCLUSION

Efficiency improvement of small rating PMBLDC motor is crucial design issue for motor designers. The initial efficiency of 85.14 % is obtained for 200 W, 24 V radial flux PMBLDC motor designed with M19-29 Ga material for stator core and teeth. The efficiency can be improved using superior quality magnetic material. The efficiency is increased from 85.14 % to 86.80 % due to less specific iron loss and high relative permeability of Hiperco magnetic material. Both designs are validated by conducting 2D FE analysis. It is analyzed that use of superior quality magnetic material enhances efficiency of PMBLDC motor. Replacement of stator core material from M19 to Hiperco improves efficiency of small rating PMBLDC motor.

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