Literature review of Brushless Direct Current Motors Topologies and its Applications

Mrs. S. D. Joshi[*], **Prof. Dr. (Mrs.) N.R.Kulkarni**[**]

PES's Modern college of Engineering, Shivajinager Pune 05. Maharashtra, India

Abstract—

Abstract - In industrial applications and electric vehicles BLDC (Motors) are being used. This paper represents categorization of BLDC motor & applications. Preliminary design of AFM as well as RFM BLDC motor along with mathematically design equations further implemented to form generalized flowchart.

Keywords—

component; - Brushless direct current (BLDC) motor, Axial flux machine, Radial flux machine

I. Introduction

Using of Permanent Magnet in electrical machines have many benefits and advantages then electromagnetic excitation These machines have zero excitation losses resulting in high efficiency, simple construction, low cost, less maintenance and high torque or high output power per unit volume. In early 19th century permanent magnet excitation system was used for first time in electrical machines. The performance of this machine was very poor due to poor quality of hard magnetic material. After the invention of alnico the use of permanent magnet excitation system increased. Rare earth permanent magnets improve the power density and dynamic performance of the machine. Induction motors are most popular machine in the 20th century due to its simple construction, less price, reasonable reliability and low maintenance. Due to small air gap, lower efficiency and low power factor than synchronous machine made synchronous machine prevalent in industrial applications. Due to high power to weight ratio, high torque, good dynamic control for variable speed applications, absence of brushes and commutator make Brushless dc (BLDC) motor [1]best choice for high performance applications. Due to the absence of brushes and commutator there is no problem of mechanical wear of the moving parts [2], [3].As well, better heat dissipation property and ability to operate at high speeds [4-5] make them superior to the conventional dc machine. Due to its high torque and efficient performance it has wide applications. [6]. It is electronically commutated with high N/T characteristics, dynamic response, efficiency, & noiseless operation.

This paper gives relevant information about design of BLDC motor topologies and its applications. In section II detail study of Topologies of BLDC motor is explained. Magnetic Circuit design of Axial flux BLDC motor and radial flux BLDC motor is explained in section III and IV. Generalized flow chart for BLDC Motor design is explained in section V. Lastly the applications of BLDC motors along with the benefits over conventional motors have been described in section VI.

II. TOPOLOGIES

BLDC motors can be categorized as, radial & axial flux motor. In RFM, the field travels radially between stator and rotor across the air gap. The radial field interacts with the axially flowing current which gives rise to a torque. BLDC motors generate trapezoidal back electromotive force (EMF) and sinusoidal back electromotive force. From this perspective, the name "brushless DC" fits even though it is an AC motor.

In AFM [7] the field is distributed axially between stator and rotor. Axial field interacts with the radial travelling current which gives rise to a torque. In RFM, magnets act against centrifugal force on the rotor.

For direct-driven motor, an AFM more advantages compared to the RFM. AFM with different configurations being adopt for better performance applications [8, 9, 10, and 11]. It is designed for higher torque-to-weight ratio with high efficiency. Compared to slotted axial flux motor, non-slotted axial flux motor has low ripple torque [11].

AFM motors are of Following Types [12]

A. Single Side type

Brief topology in the AFM slot and slot less is shown below:

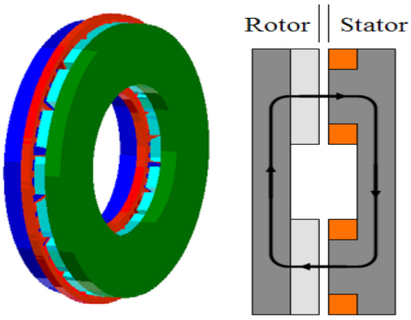

Fig.1 Single rotor single stator structure

B. Double Side type

This topology represents double sided motor in two ways :

- Two stators contains sandwiched rotor or vice versa.
- AFM, slot less, disc type structure.

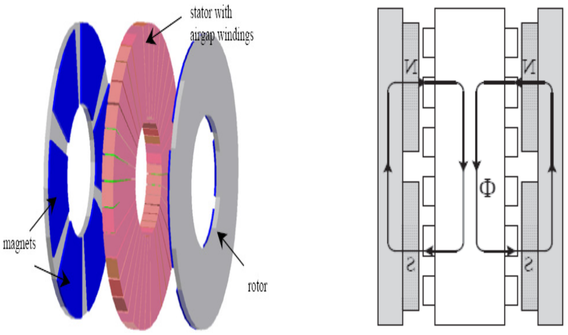

Fig.2 Two rotor single stator structure

C. Multistage type

Fig.3. shows the stators are formed by non-slotted strip wound stator steel. Back to- back connected gramme type air gap windings are again placed around the stator core.

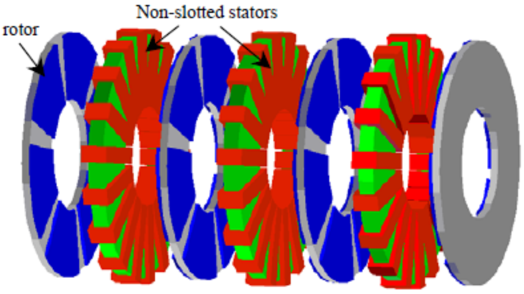

Fig.3. Slot less Multi Stage PM Machine

The outer rotor discs are formed by both rotor cores and axially magnetized surface mounted magnets as in other TORUS type topologies. The inner rotors are formed by rotor discs with permanent magnets on both sides of the rotor core.

III. AXIAL FLUX BLDC MOTOR

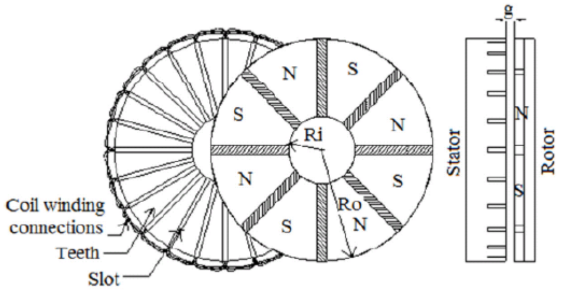

Fig.4 shows the AFM topology showing geometrical definitions. The Leaving flux divides by two from the center magnet and enters through air gap into the two adjacent magnets, stator iron and returns through air gap and rotor iron as shown in Fig. 5

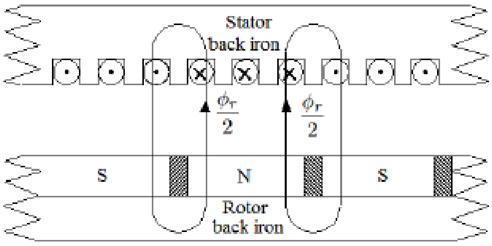

Fig 5.Magnetic path

The magnetic circuit for this flux loop is presented in Fig.6

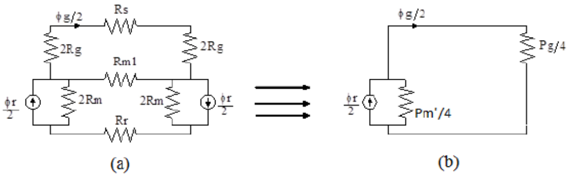

Fig. 6 (a) Axial BLDC motor magnetic circuit (b) simplified one.

As motor consist of disc shaped rotor with PM pasted on surface facing the stator. Air Gap Flux given by:

$$\varphi_g = \frac{1}{1 + \frac{P_{m'}}{P_g}} \varphi_r \qquad (1)$$

Where

P_g : air gap permeance

P_{m}`: quivalent permeance ($P_m + P_m$l).

eq 1 can be rearranged as

$$\varphi_{g}=\frac{1}{1+\frac{\mu_r K_c K_m l}{P_c}} \qquad (2)$$

Where

P_c :permeance coefficient,

K_c : crater coefficient and

K_m l: magnet leakage factor.

$$Pc=lm/2c*g \qquad (3)$$

Cφ : Flux concentration depends on (Ag) area of air gap and (Am) area of magnet.

$$c_\varphi = \frac{A_m}{A_g} \qquad (4)$$

In Axial flux BLDC motor, magnetic area can be found as

$$Am = \int_{Rt}^{Ro}(2\pi(r - \Delta r) \qquad (5)$$

Motor is having trapezoidal back emf, is then written as

$$E_b = N_m K_d K_p K_s B_g N_{spp} n_s (R_o^2 - R_i^2)\omega_m \qquad (6)$$

Where,

K_d: Distribution factor

K_p : Pitch Factor

K_s : skew factor,

N_m : number of poles ,

N_{spp} : number of slots/pole/phase

n_s : number of turns/slot.

Constant of back emf expressed as:

$$K_e = 2\, N_m K_d K_p K_s B_g N_{spp} n_s (R_o^2 - R_i^2) \qquad (7)$$

Developed Tem is given by

$$T = K_e I \qquad (8)$$

I : dc coil current. [13]

IV. Radial Flux BLDC Motor

Fig 7 represents RFM which consists of stator consists of laminated stampings and rotor with surface mounted magnet configurations.

Conventional design method

To identify the performance of motors when dimensions are known conventional methods are used generalized performance equations for design of Surface mounted Permanent magnet motors described by Slemon.

The approximate expression for torque and losses has been derived. [14]

$$T = 2pr2lBgJ_s \text{ sinf} \qquad (9)$$

J_s: linear current density.

r: rotor radius.

l: rotor length.

Bg : air gap flux density.

f: displacement angle between fields

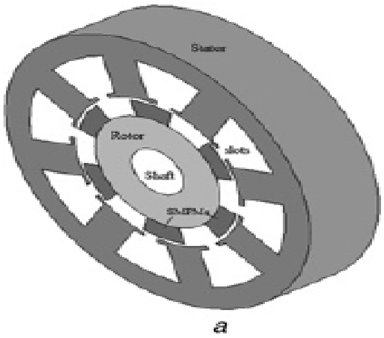

Fig. 7 Conventional RFSMPM machine

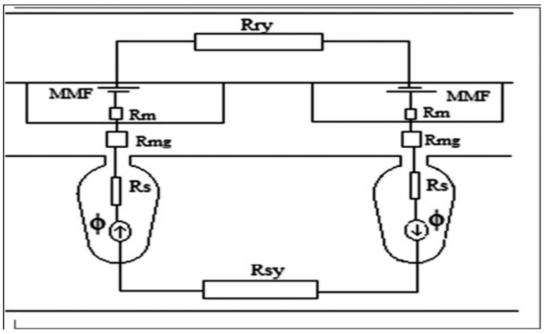

Fig.8 MEC equivalent model of a PM machine

For a single pole RFSMPM machine [15]

For modeling flux density distribution of PM machines MEC is used. The flux between nodes as shown in Fig.8.

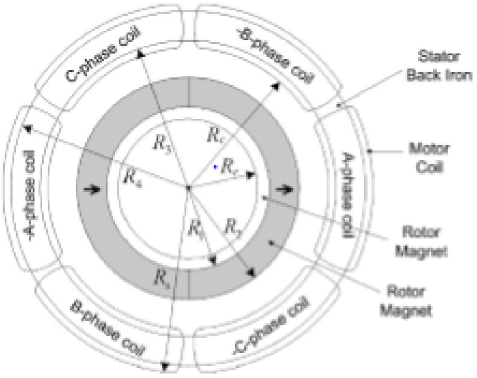

Fig. 9. Schematic view of a RFM

The different reluctance parameter is given by:

Rry: rotor yoke

Rsy: stator yoke

Rm: PM

Rmg: stator and rotor air gap

Rs: slots.

The coil windings are wound toroidally carries stator ring which is surrounded by R3 and R4 [16].

Machine consists of uniform field variables in an axial direction, so that magnetization vector of permanent magnet represented in Fourier series,

$$\mathbf{M}(\theta_e) = \frac{4B_{\text{rem}}}{\pi\mu_0} \sum_{n=1}^{\infty} \frac{1}{n} \sin(n\theta_{\text{me}}/2) \cos n\theta_e \hat{\mathbf{r}} \tag{9}$$

Where,

B_{rem} : magnetic flux density.

Let machine is two-pole type, then air gap field will be very close to a sinusoid, and the magnetization vector, expressed as:

$$\mathbf{M}(\theta) = M_0 \cos\theta \hat{\mathbf{r}}. \tag{10}$$

L'Hospital's theorem is used to identify radial flux density in air gap expressed as:

$$B_r = \beta_0 \rho_1 \left[1 + \left(\frac{R_3}{r}\right)^2\right] \cos\theta \tag{11}$$

Value of ρ_1 is

$$\rho_1 = \frac{1}{2}(R_2^2 - R_1^2) + R_1^2 \log\left(\frac{R_2}{R_1}\right). \tag{12}$$

Design of back iron is done in such a way that the flux density in the iron is kept below the saturation density. Thus flux per unit depth is obtained from

$$\phi_{\max} = \int_0^{\pi/2p} B_r(R_3) R_3 d\theta. \tag{13}$$

Expression for flux density is

$$B_{\text{sb}} = \frac{\phi_{\max}}{R_4 - R_3} = \frac{2\beta_0\rho_0 R_3}{R_4 - R_3}. \tag{14}$$

The generated torque from Lorentz force given

$$T_a = \iint_{A_c} \mathbf{r} \times (\mathbf{j} \times \mathbf{B}) da \tag{15}$$

The current density of the coil given by,

$$j = \frac{2N_a I_a}{(R_3^2 - R_c^2)\,\theta_c} \tag{16}$$

The radius factor k_r is defined as

$$k_r = \frac{\rho_0}{(R_3^2 - R_c^2)\left(R_3^{2p} - R_1^{2p}\right)} \times \left[\frac{1}{2+p}\left(R_3^{2+p} - R_c^{2+p}\right) + \frac{R_3^{2p}}{2-p}\left(R_3^{2-p} - R_c^{2-p}\right)\right]$$

radius factor torque can be written as,

$$T_a = k_b k_r (\mu_0 M_0) N_a I_a \cos p\theta_a. \tag{17}$$

The total torque is

$$T = 2pk_b k_r B_0 \sum_{q=a,b,c} N_q I_q \cos p\theta_q \tag{18}$$

V. GENERALIZED FLOWCHART FOR PM BLDC MOTOR

Design procedure of PMBLDC motor includes main four steps i.e. calculation of main dimensions, stator design, rotor design and calculation of performance parameters. In addition to that two corrective loops are introduced in the flowchart. Inner loop is for correcting air gap flux density and outer loop is for calculation of efficiency [17].

As shown in Fig. 10,

- Using current and N, the slot area & dimensions are calculated.
- Performance parameter is calculated and it should meet the desired parameter. If the required parameter matches with tolerance afterwards FEA begins.

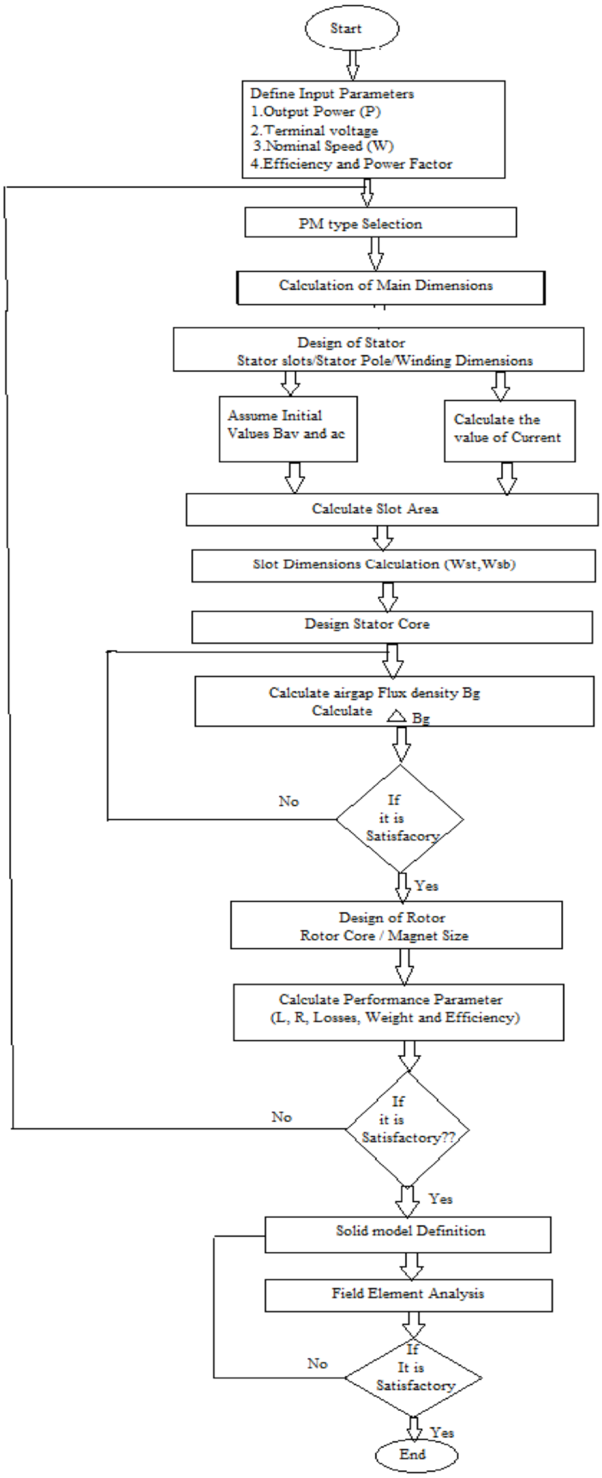

Fig.10 PMBL MOTOR design flowchart.

If above statement not satisfied then R, L, B and/or even motor configuration and magnetic material type may be changed as per requirement. [18].

VI.APPLICATIONS

Many applications require high torque, high efficiency, economic feasibility, Compactness and Space factor which is fulfilled by BLDC motor. Few applications of BLDC motor are listed as below

A. Wind Power Systems

AFM synchronous generator can be used for low-speed wind turbine applications.

B. Electric Vehicles

AFM motors due to compactness, robustness, high efficiency, and high torque are used in electrical vehicles.

C. Blowers

In AFM is designed for blowers in vacuum cleaners [19]

D. Heating and Ventilation

HVAC systems use brushless motors because microprocessor allows programmability, control over airflow. [20]

E. Industrial Engineering

The application of brushless DC motor within industrial engineering primarily focuses on industrial automation design. The most common uses of BLDC motor in industrial engineering are linear motors, feed drives and extruder drive motors for CNC machine tools .[21]

F. Positioning and Actuation Systems

For assembly robots, brushless motors are used to position a part for assembly or a tool for manufacturing process such as welding or painting. Such motors can be useful to drive linear actuators. [22] and [23]

G. Solar Race Cars

Due to Low torque and low/medium speed applications AFM motors are used. [24]

REFERENCES

1. R. Civilian and D. Stupak. 1995. Disk drive employing multi mode spindle drive system. US patent 5471353, Oct 3.
2. G.H. Jang and M.G. Kim. 2005. A Bipolar-Startingand Unipolar-Running Method to Drive an HDD Spindle Motor at High Speed with Large Starting Torque. IEEE Transactions on Magnetics. 41(2): 750-755, Feb.
3. E. Grochowski and R.F. Hyot. 1996. Future trends in hard disk drives. IEEE Tran. On Magnetics. 32(3):1850-1854, May.

4. J.D. Ede, Z.Q. Zhu and D. Howe. 2001. Optimal split ratio control for high speed permanent magnet brushless DC motors. In 5th Proceeding
5. S.X. Chen, M.A. Jabbar, O.D. Zhang and Z.J. Lie.1996. New Challenge: Electromagnetic design of BLDC motors for high speed fluid film bearing spindles used in hard disk drives. IEEE Trans.Magnetics. l32(5): 3854-3856.
6. D.C.Hanselman,"Brushless permanent motor design," New York: McGraw-Hill,1994.
7. F. Chimento and A. Raciti, "A low-speed axial-flux PM generator for wind power systems," IEEE International Symposium on Industrial Electronics, 2004., vol. 2, May 2004, pp. 1479–1484.
8. A. Cavagnino, M. Lazzari, F Profumo, A. Tenconi, "A comparison between the axial flux and the radial flux structures for PM synchronous motors", Industry Applications, IEEE Transactions on. Volume 38, Issue 6, Nov.-Dec. 2002 Page(s):1517 - 1524
9. F.Caricchi, F. Crescimbini, E. Santini, C Santucci, "Influence of the radialvariation of the magnet pitch in slotless permanent magnet axial flux motor" Industrial Application Conference, 1997.
10. Jacek F. Gieras, Ron-Jie Wang, Maarten J. Kamper, Axial Flux Permanent Magnet Brushless Machine, Kluwer Academic Publishers,Nederland, 2004.
11. M. Aydin, S. Huang and T.A. Lipo, "Torque Quality and Comparison of Internal and External Rotor Axial Flux Surface Magnet Disc Machine",IEEE IECON2001, 27th Annual Conference of IEEE Industrial Electronics, Denver, CO, Nov 29-Dec, 2001
12. Amruta Patki, "Design, Fabrication and Control of an Axial Flux Type BLDC motor" M.Tech. thesis, Dept. Elect. Eng., Nagpur Univ., Nagpur, Maharashtra, 2014.
13. Sreeju S Nair, ShamsuddeenNalakath, Member, IEEE, and SamrajJabezDhinagar, Member, IEEE,"Design and Analysis of Axial Flux Permanent Magnet BLDC Motor for Automotive Applications",IEEE International Electric Machines and drives conference(IEMDC),2011
14. Wu, L.J., Zhu, Z.Q., Staton, D., et al.: 'Comparison of analytical models for predicting electromagnetic performance in surface-mounted permanent magnet machines'. IEEE Vehicle Power and Propulsion Conf. (VPPC), 2010, pp. 1–6
15. Wu, L.J., Zhu, Z.Q., Staton, D., et al.: 'An improved subdomain model for predicting magnetic field of surface-mounted permanent magnet machines accounting for tooth-tips', IEEE Trans. Magn., 2011, 47, (6), pp. 1693–1704.
16. Hak-In Lee and Myounggyu D. Noh, Member, IEEE "Optimal Design of Radial-Flux Toroidally Wound Brushless DC Machines", IEEE Transactions on Industrial Electronics Vol. 58, NO. 2, Feb 2011.
17. Amit N.Patel, Nirav Patel, Pranay Patel "Genetic Algorithm Based Multi-Objective Design Optimization of Radial Flux PMBLDC Motor".
18. O. Safdarzadeh, M. Mahdavyfakhr, E. Afjei ,"An Adaptive Algorithm for PMBL Motor Design ", 8th Power Electronics, Drive Systems & Technologies Conference (PEDSTC 2017).
19. Anurag Khergade, B. Bodkhe Closed Loop Control of Axial Flux Permanent Magnet BLDC Motor for Electric Vehicles 978-1-5090-0128-6/16/ ©2016 IEEE
20. Soma sundaram B , Ashok Kumar L , Banu Rekha B , Hemanand R, "Study On Energy Efficiency and Harmonics Mitigation In A HVAC Ahu Blower/Fan Application Using Electronically Commutated BLDC Motors", Journal of Electrical Engineering.
21. Ohio Electric Motors. "Brushless DC Motors Used in Industrial Applications". Ohio Electric Motors.2012.
22. Shimon Y.Nof, Wilbert E. Wilhelm and Hans-Jurgen Warnecke. "Industrial assembly" Springer,1997
23. M. Gopal. Control Systems: principles and design.2nd ed. Tata McGraw-Hill, 2002.
24. R.Al Zaher, S.de Groot, H.Polinder, P.Wieringa, "Comparison of An Axial Flux And A Radial Flux Permanent Magnet Motor For Solar Race Cars",International Conference on Electrical Machines- ICEM 2010.