International Journal on Emerging Technologies **11**(2): 468-474(2020)

ISSN No. (Print): 0975-8364
ISSN No. (Online): 2249-3255

An Innovative Methodology in Design of a Permanent Magnet Brushless DC Motor for a Particular Application

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(Received 23 December 2019, Revised 16 February 2020, Accepted 18 February 2020)
(Published by Research Trend, Website: www.researchtrend.net)

ABSTRACT: Now-a-days permanent magnet brushless DC motors are notable for their strength because of its performance in terms of efficiency, Speed-Torque charterstics, size and power density. These permanent magnet brushless DC motors are widely used in various applications like automobiles, air-crafts, domestic applications etc. These motors are used in low, medium and high power applications. This paper presents complete design procedure for permanent magnet brushless DC motor for a particular application by considering various factors like slot and pole combination, cost analysis, relationship among various design parameters and complete design procedure from starting to end. In the present day scenario the permanent magnet brushless DC motors are familiarly used in various domestic, commercial and Industrial applications. The major challenging issue is design of motor with higher power density. In this regard the present paper proposes the complete design considerations by considering various parameters along with cost analysis and layouts in order to achieve higher power density. This paper also presents the relationship among various design parameters using MATLAB.

Keywords: Brushless DC motor, Efficiency, Slot and Pole.

Abbreviations: DC, Direct Current Motor.

I. INTRODUCTION

In general brushless DC motor is basically PM motor with stator and rotor structures. There are two types of BLDC motors; they are inner rotor motor and outer rotor motor. They are more efficient because of the absence of commutator and brushes [12]; it requires less maintenance and smaller in size. The various applications of these motors are radiator fans, heater blower fans, water pump, etc., where available volume is less.

The poles in permanent magnet Brushless are always even and the number of slots may be any integer value. But one cannot assign any number of slots for the desired number of poles; there is a certain combination of slots and poles, which lead to efficient torque production. The motor performance depends on the winding coefficient. The range of winding coefficient is unity or less than unity [1]. The performance of the machine depends upon the winding coefficient. For a BLDC motor, the winding pattern is fixed based on the slot and pole number and other dimensional parameters. By selecting proper winding structure, one can reduce the volume of copper required at the end windings; Joule losses are decreased so that the efficiency will be increased [2]. In order to have balanced winding the shape and magnitude of electro motive force and relative phase difference between phases need to meet the requirement. The adequacy and state of the phase back EMF's will be indistinguishable if the coils in each stage have a similar number of turns and a similar coil span and are distributed similarly around the stator [13]. The back emf of each phase ought to be 120 degrees electrical [11].

The limitations of the various papers presented in the literature are they confined to a particular application like Electric Water Pump [5], Centrifuge [7], electric power steering (EPS) [9], kick scooter [10], and applications. But in general, there are different types of loads like constant load, varying load, and some positioning applications. These loading conditions are not taken into consideration in the literature. The present paper proposes a generalized design strategy applicable to various types of applications along with performance analysis (SPP, SPP/Phase, and K_W) by considering temperature rise. The present paper proposes a complete design methodology for any type of application which may be used in domestic, commercial and Industrial application by considering slots and pole combinations, cost analysis and relationship among various design parameters in order to achieve higher efficiency and power density.

II. DESIGN METHODOLOGY OF PMBL DC MOTOR

The design approach of the motor will start from the application of the motor. Based on the output requirement, the various factors like stator inner and outer radius, magnetic area, slot pitch, tooth width, thickness of the housing frame, air gap length etc. along with electrical parameters like dc bus voltage, current, current density are need to be determined before realisation of the motor.

Steps to design the motor:
Step: 1 Determination of the physical size of the motor
Step: 2 Determination of available input
Step: 3 Selection of Poles, slots, teethes and phases
Step: 4 Identification of input for the desired output
Step: 5 Determination of losses

Step: 6 Determination of current and resistance from speed- Torque point
Step: 7 Identification of magnetic circuit components
Step: 8 Determination of stack length
Step: 9 Determination of the size of the wire
Step: 10 Determination of the number of turns
Step: 11 Determination of magnetic circuit
Step: 12 Determination of performance and evaluate design.

A. Mathematical Modelling to Determine Motor **Ratings and Dimensions:** The complete mathematical modelling of PM brushless DC machine is as follows

$$B = \mu H \quad (1)$$

Force is given by

$$F = \phi R \quad (2)$$

R is the reluctance of the machine
Torque is given by

$$T = KD^2L \quad (3)$$

Reluctance is given by

$$R = \frac{1}{\mu A} \quad (4)$$

A is the area of cross-section
Flux is given by

$$\phi = \frac{NI}{R} \quad (5)$$

Maximum flux density of the machine is given by

$$B_m = B_r + \mu_0\mu_r H_m \quad (6)$$

B_r is the flux density of rotor.
Flux of the permanent magnets is given by

$$\phi = B_m A_m = B_r A_m + \mu_R\mu_0 A_m H_m \quad (7)$$

Flux linkage of the coil is given by

$$\lambda = \frac{N^2}{R} i \quad (8)$$

Induced voltage is given by

$$e = L\frac{di}{dt} \quad (9)$$

Torque equation is given by

$$T = \frac{1}{2} i^2 \frac{dL}{d\theta} - \frac{1}{2}\phi^2 \frac{dR}{d\theta} + Ni\frac{d\phi}{d\theta} \quad (10)$$

The Inductance of air gap is given by

$$L_g = \frac{2\pi\mu_0 L_{st} R_{ro}}{g + \dfrac{l_m}{\mu_R C_\phi}} N^2 \quad (11)$$

Motor constant K is given by

$$K_m = \frac{2NB_g L_{st} R_{ro} I}{\sqrt{I^2(2R_{slot})}}$$

$$\Rightarrow \frac{2NB_g L_{st} R_{ro}}{\sqrt{2\rho L_{st} N / A_{wb}}}$$

$$\therefore K_m = \frac{B_g R_{ro}}{\sqrt{\rho}}\sqrt{V_{wb}} \quad (12)$$

Cogging Torque is given by

$$T_{Cog} = -\frac{1}{2}\phi^2\frac{dR}{d\theta} \quad (13)$$

Ultimately from the above equations, one can determine the dimensions of the permanent magnet brush less DC machine. Several other factors like springing effect, Proximity effect, and effect of eddy current are need to be considered before the design of the machine [7-8].

B. Selection of Slot number for a given number of poles
The number of poles in a permanent magnet Brushless DC motors must be even values for any number of slots. But one cannot assign any number of slots for the desired value of poles; there is a certain combination of slots and poles, which lead to efficient torque production. If the slots are not appropriately selected, then all slots will not be filled with the two coil sides, which are undesirable conditions [3]. Initially, the numbers of rotor poles are selected based on the nominal speed for a required application.
For having a high winding factor and higher motor performance, the number of slots must be equal to the number of poles. But it is difficult to have a poly-phase structure with criteria.
Various combinations of slots and poles for a balanced winding are determined by

$$3k = \frac{S}{HCF\,(s, 2P)} \quad (14)$$

Where S is the slot number, 2p is pole number and k is constant.
Procedure to check whether the assumed number of slots are satisfied for given poles or not
Let number of poles: 2. Slots: 2.
First check for K=1
HCF of (2, 2) =1; Equating the respective values in Equation-1, we have 1≠3.
Similarly, check for any value of K then LHS≠RHS. Hence for 2 poles, it is not efficient to have 2 slots.
Now let us consider that the number of slots is 3.
For k=1;
HCF of (3, 2) =1; Equating the respective values in Equation-1-1 we have 3=3. Hence for 2 poles, one can have 3 slots for having efficient torque production.
The number of SPP value is given by

$$3k = \frac{S}{HCF\,(s, 2P)} \quad (15)$$

The motor performance is more efficient at S = 2p
In general, before the synthesis of permanent magnet brushless DC machine one cannot select the slot and pole combinations randomly because some of the combinations lead to in efficient operation.

C. Determination of winding coefficient
The winding coefficient is the key parameter in the design of permanent magnet brushless DC motor. It is denoted as Kw. This coefficient is used for determining the efficient winding armature of a motor. It is the performance indicator of a motor. The range of the Winding coefficient is unity or less than unity [4]. The efficiency of the machine is more if the winding factor is nearer to unity.
In order to determine the winding coefficient, initially, the S to 2p ratio is considered. From the winding coefficient versus slots per pole plot, one can determine the corresponding winding factor value for the ratio of S to 2p.
Winding Co-efficient $K_w = K_d \times K_p$ (16)
where K_d is the distribution factor and K_p is pitch factor.
Let the distribution factor K_d=1. The value of K_P is selected on the basis of the ratio of slots to the pole ratio.

Case (i): For S>P

$$K_P = \cos\frac{\left(180 - \frac{180}{\frac{S}{P}}\right)}{2}$$

(17) Case (ii): For $S < P$

$$K_P = \cos\frac{\left(\frac{180}{\frac{S}{P}} - 180\right)}{2} \qquad (18)$$

Case (iii): For $S = P$

The pitch factor value is 1.

From Fig. 1, one can observe that the structure which offers the best winding coefficients has the S nearer to P. The generalized way of determining the slots for having a higher winding coefficient is at values of slots nearer to P±1; P±2; P±3.

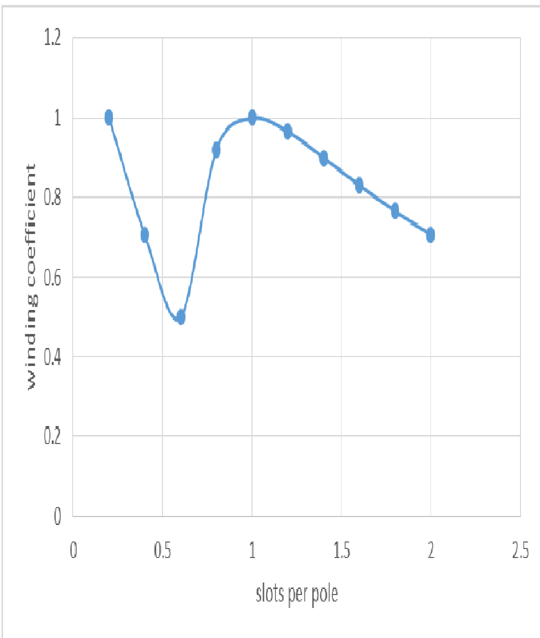

Fig. 1. Variation of winding coefficient with slots per pole.

D. Determination of Winding configuration

After selecting the number of slots, poles and winding coefficient is to be fixed for the winding configuration. With the designed winding structure, one can reduce the volume of copper required at the end windings; total losses are reduced, thereby increasing efficiency. The induced electromotive force amplitude shape and relative phase difference should be same in order to get balanced winding [5]. The sufficiency and shape of the phase back EMF's will be indistinguishable if the coils in each stage have a similar number of turns and an identical coil spans and are conveyed similarly around the stator [6]. The back emf of each phase should be 120 degrees electrical [7].

The winding configuration involves the following steps:

Step 1: The SPP (slots per pole per phase) is reduced to a decimal value.

Step 2: For determining the layers (i.e., first and second layer) take two values, namely 0's and 1's.

Step 3: From the ratio of (x/y), Integer 'y' has 0's and 1's where the number of 1's is equal to the integer 'x'.

Step 4: Then, the starting alternating sequence of Zero's and One's are composed.

Step 5: Then, this sequence arranged in an optimal way.

Step 6: Then, this optimal repeatable sequence is reproduced for x times.

Step 7: Then, the general sequence is enhanced to total sequence. First of all phase A is obtained then after 120ºE phase B is taken followed by phase c 120º E from phase B. Then it said to have a relative phase sequence, for having a proper balanced winding. The A', B' and C' are for return Conductors. The A' will 180ºE to the A phase. Similarly, B' and C' are 180ºE to B and C phase respectively.

Step 8: The conductors associated with 1's are chosen for the first layer of the winding.

Step 9: Then the second layer is determined by repeating and transforming by width.

III. PERFORMANCE ANALYSIS

A. Performance Analysis of PMBLDC machine for various slot and pole configurations

Distinctive parameters, for example, the S & P values, the winding structure, and cost analysis need to be analysed before realisation of the actual motor.

The following indices can explain the performance analysis of the entire BLDC motor.

– Winding factor
– Voltage distortion
– Fault tolerance
– Leakage Inductance
– Force on rotor

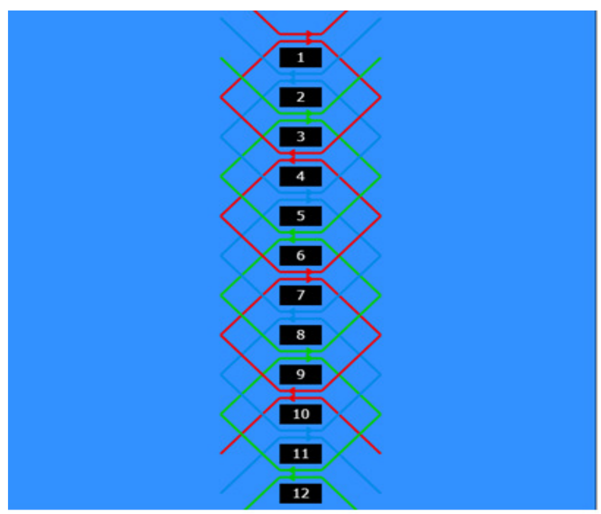

Fig. 2. The winding layout of 12 Slots and 4 poles BLDC motor.

The conceivable S/P ratio, SPP and winding factor blends of a different number of P and S values have been broke down for a specific motor (Fig. 2). The chance of the mixes alongside the design parameters like Slots per pole, SPP, and K_W are depicted in Table 1. In light of the recognized application, one can choose the slot-pole combination of the motor.

B. Cost Analysis

The possible cost in rupees is analysed for various slot and pole combinations for a particular motor.

The cost in rupees, along with the winding factor, is presented in Table 2. From the above table, one can select the optimum slot- pole combination by considering the cost and winding factor. The winding factor implies the efficiency of the motor indirectly.

$$Y_1 = g_1X_1 + g_2X_2 + g_3X_3 \quad (19)$$

where g_1, g_2, and g_3 are the weights of the material and these are considered as $g_1 = 0.3$, $g_2 = 0.35$ and $g_3 = 0.35$.

And the values of X_1, X_2, and X_3 are given by

X_1= Material Cost * Weight of Material

X_3= no. of Slots * Cost for slotting

X_2= no. of Poles * Cost for Poling

While selecting the combination of optimal slot and pole combination, the proposed paper considers the economic aspects also to reduce the price in design aspects.

Table 1: Performance analysis of the machine for various slots and poles combinations.

S/P	2	6	12	24	32	40	48	Remarks
3	1.5 0.5 0.866	Not Possible	Not possible	Not possible	0.09375 0.03125 0.866	0.075 0.025 0.866	Not possible	SPP SPP/Ph K_W
9	4.5 1.5 0.365	1.5 0.5 0.866	0.75 0.25 0.866	0.375 0.125 0.866	0.28125 0.09375 0.6427	0.225 0.075 0.6427	0.1875 0.0625 0.866	SPP SPP/Ph K_W
18	9 3 0.132	3 1 0.5	1.5 0.5 0.866	0.75 0.25 0.866	0.5625 0.1875 0.328	0.45 0.15 0.328	0.375 0.125 0.866	SPP SPP/Ph K_W
27	13.5 4.5 0.116	4.5 1.5 0.365	2.25 0.75 0.617	1.125 0.375 0.945	0.84375 0.28125 0.902	0.675 0.225 0.727	0.5625 0.1875 0.328	SPP SPP/Ph K_W
33	16.5 5.5 0.095	Not possible	Not possible	Not possible	1.031 0.34375 0.9988	Not possible	0.6875 0.229 0.7557	SPP SPP/Ph K_W
42	21 7 0.0747	Not possible	Not possible	Not possible	1.3125 0.4375 0.9308	1.05 0.35 0.953	Not possible	SPP SPP/Ph K_W
54	27 9 0.058	9 3 0.132	4.5 1.5 0.365	2.25 0.75 0.6427	1.6875 0.5625 0.802	1.35 0.45 0.878	1.125 0.375 0.945	SPP SPP/Ph K_W

Table 2: Cost analysis of machine for various slots and poles combinations.

S/P	2	6	12	24	32	40	48	Remarks
3	182 0.816	372 —	657 —	1227	1607 0.866	1988 0.866	2367 —	Y K_w
9	356 0.365	546 0.866	831 0.866	1401 0.866	1781 0.6427	2161 0.6427	2541 0.866	Y K_w
18	617 0.132	807 0.5	1092 0.866	1662 0.866	2042 0.328	2422 0.328	2802 0.866	Y K_w
27	878 0.116	1068 0.365	1353 0.617	1923 0.945	2303 0.902	2683 0.727	3063 0.328	Y K_w
33	1052 0.095	1242 —	1527 —	2097 —	2477 0.9988	2857 —	3237 0.7557	Y K_w
42	1313 0.0747	1503 —	1788 —	2358 —	2738 0.9308	3118 0.953	3498 —	Y K_w
54	1661 0.058	1851 0.132	2136 0.365	2706 0.6427	3086 0.802	3460 0.878	3846 0.945	Y K_w

IV. RESULT ANALYSIS

A. Design of radial flux motor

Fig. 3 demonstrates the design outline of a permanent magnet brushless DC machine. These frameworks are ordinarily used for various applications like mixer grinders, aerospace applications, etc. [4]. The most troublesome part is the structure of a stator since the design itself made wingdings difficult to wind. With this particular design, the rotor setup can be changed if essential. The general shape/structure for the machine has been developed based on the kind of material going to be used [5].

With higher magnetic flux, there is a progressively noticeable magnetomotive force, which substantially achieves more prominent magnetic field intensity. The goal is to expand the magnetic flux linkages. Remembering the ultimate objective to increase the flux, the more magnetic flux density is required [6]. The more noticeable the magnetic field, the more grounded constrain the magnets must be pulled in or repelled. All things considered, the material must be found that was reasonably assessed and could give the pined for magnetic flux density. Fig. 4 presents the winding layout of permanent magnet brushless DC machine.

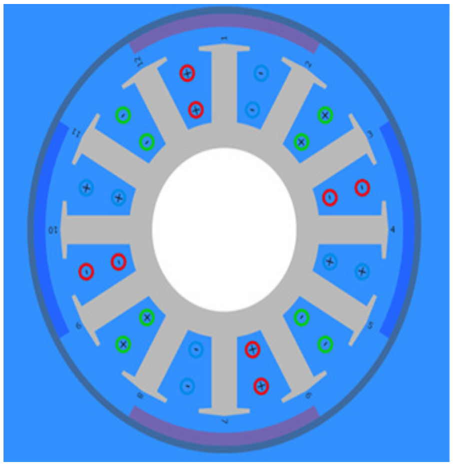

Fig. 3. Design of radial flux motor.

B. Stator Dimensions
The stator dimension of permanent magnet brushless DC motor by considering various stator parameters like slot width, stator back height, stator outer and inner radius as shown in Fig. 4.

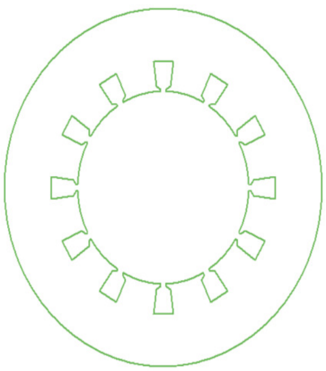

Fig. 4. Stator with Slots.

C. Slot Dimensions
The slot dimensions of permanent magnet brushless DC motor with various parameters are illustrated in Fig. 5.

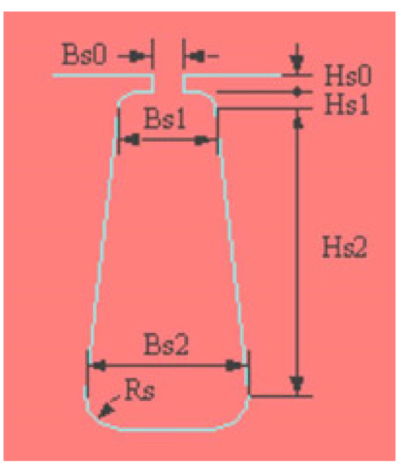

Fig. 5. Slot Dimensions.

D. Simulation performance of the PM BLDC machine
The supposed slots and coils in the corresponding phase that should be used with a certain number of poles, the analysis of the operating torque, or rotor reacting torque from each conductor is analysed as its electromagnetic flux is cross-linked with the permanent magnetic flux of the rotor.
The permanent magnet pole arc length is very important, and the uniformity of the flux density across the surface of the magnet has a significant effect on the torque produced of one phase as the rotor rotates. The structure of the rotor is as shown in Fig. 6.
Final outline of complete machine, which is designed, is illustrated in Fig. 7.

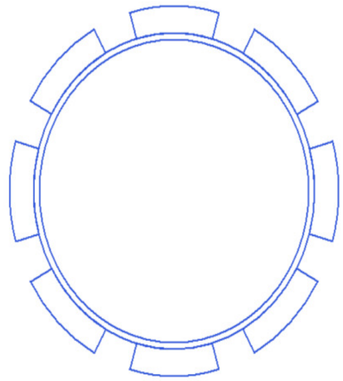

Fig. 6. Rotor (Type-1).

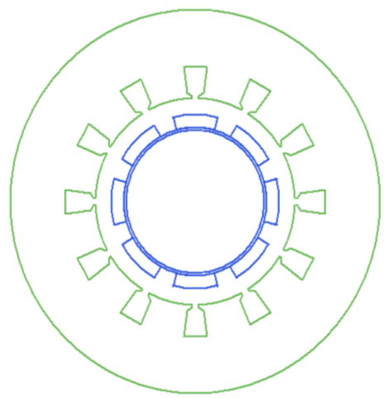

Fig. 7. BLDC motor Cross-Section.

The MATLAB simulations among various parameters along with interrelationships are illustrated in Fig. 8 and 9. Fourier series method is used to analyse the field distribution results in generating the motor back electro motive force. A plot of the waveform is then outputted for one phase as a function of a rotor pole pair rotation. This can enable the designer to analyse many slot/winding configurations. Skewing of the rotor poles and stator slots can also be investigated. Such modeling methods save considerable cost and time with the added benefit of revealing some very useful and not so distinct slot/pole combinations. The analysis is performed for this particular design with the variation among the parameters.
It is developed at a constant diameter and constant volume, for a particular application as illustrated in Fig. 8 and 9.
The relationship between various parameters is identified and analysed.

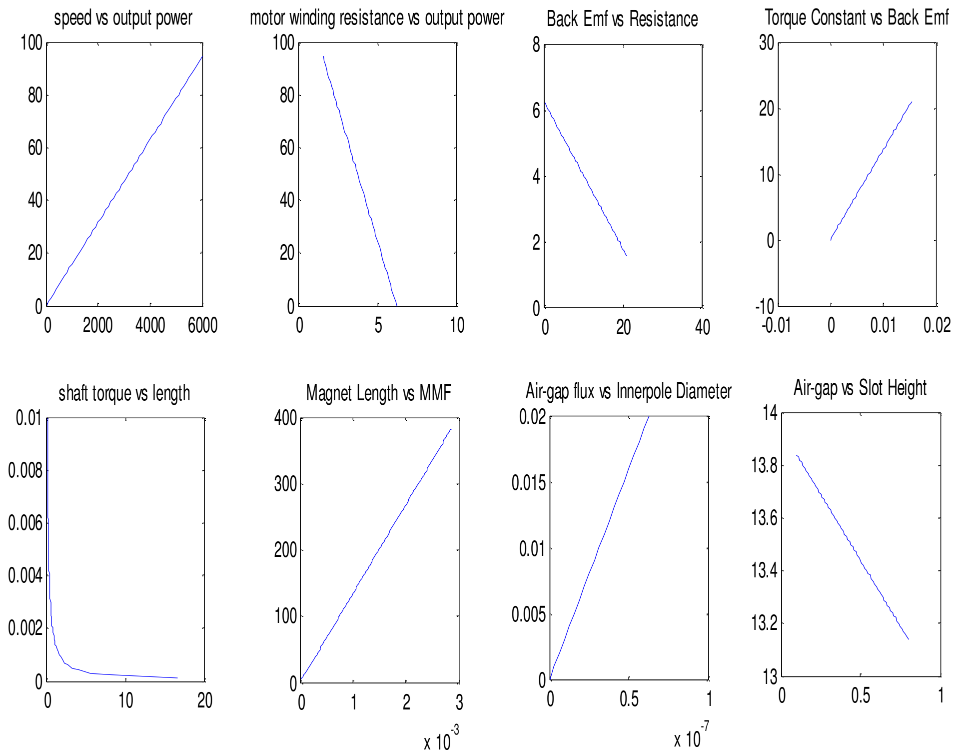

Fig. 8. Variation of various parameters at constant diameter.

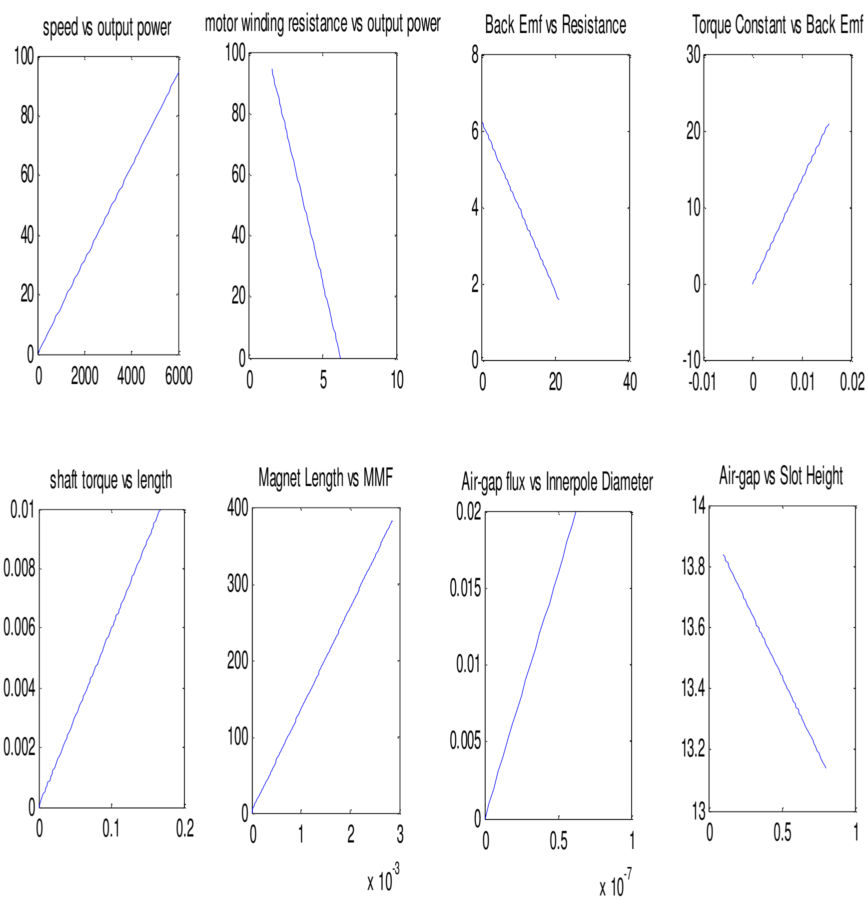

Fig. 9. Variation of various parameters at constant volume.

V. CONCLUSION

This paper exhibits the structure and execution information of the machine for the immediate drive impetus framework. The machine has been explicitly intended to meet the prerequisites. From the above examination, the various quantities of slots and pole combinations are resolved. In the event that the quantity of S is equal to P, at that point, machine execution will be progressively proficient. The Winding coefficient is the exhibition pointer of a machine. If the winding coefficient is nearer to unity, then the efficiency of the motor is more. The scope of the winding coefficient is 1 or less than 1. All in all, for a permanent magnet brushless DC machine, one can lean toward fractional slot concentrated winding. Mathematical means of determining various parameters required to properly layout coils, especially in the multi-phase winding, had been specified in this article. Thus the aim of the author(s), which is a practical interpretation of design paradigms which eventually leads to physical construction, had been achieved. This approach can be applied to any slotted electrical motor irrespective of S and P values.

The realization of a permanent magnet brushless DC machine system is analysed. The mathematical modeling and simulation analysis are performed in the proposed paper.

Design analysis is performed with various slots and poles combinations along with the cost analysis and the corresponding winding factor. One can select the slot and pole combination before the synthesis procedure.

VI. FUTURE SCOPE

The present paper proposes the complete design methodology of a permanent magnet brush less DC motor for a particular application. Further based on the design parameters one can select the optimal value of the individual parameters by considering the overall objective function in between the predefined limits so that actual realisation of motor is easy for the designer.

Conflict of Interest. The authors confirm that this article contents has no conflict of Interest.

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How to cite this article: Potnuru, U. K. and Rao, P. M. (2020). An Innovative Methodology in Design of a Permanent Magnet Brushless DC Motor for a Particular Application. *International Journal on Emerging Technologies*, *11*(2): 468–474.