

# Design of Bldc Motor for Agriculture Pump Application

Mahendra G, Sakthivadivel D, Vijayakumari A

**Abstract:** This paper presents the analytical design method for surface mounted BLDC motor to meet the performance requirements of submersible Pump for agriculture application. The design calculations commence with the assumption of various design variables viz. Stacking factor, leakage factor, Flux densities in stator and rotor yokes and flux density in the stator teeth etc. To derive the geometry of the intended motor. The geometrical information like the rotor diameter, rotor and stator thickness and stator teeth thickness etc. obtained from the analytical calculations are used as input to FEM Analysis tool (FEMAG). The Torque-Speed characteristics, back EMF, flux densities in various parts of the motor obtained from FEM Analysis are compared with the results obtained from Analytical design. Based on analytical models and FEM Analysis, 18slot 6 pole BLDC motor for agriculture pump is designed and also influence of various parameters like airgap, stack length and magnet width are studied using FEM Analysis.

**Index Terms:** BLDC motor, Agriculture submersible pump, permanent magnet motors, FEM analysis.

## I. INTRODUCTION

Design of BLDC motors gained a momentum in the recent past across various applications which include grinders, Electric cycles, aerospace and many more. Such an acclaim is due to its high efficiency and high power density which in turn made BLDC a suitable contender for energy efficient motor drives. In India the widespread induction motor based agriculture water pumps if replaced with energy efficient BLDC motors can contribute for the curtailment of a substantial amount of demand on our electric utility. BLDC motor is designed for a submersible oil pump in [5] where, the rotor backward fixing method is adapted for reducing the cogging Torque. In [12], a multipolar permanent magnet synchronous submersible motor (MPMSSM) for screw pump have been discussed. A new rotor design is proposed and the structures of stator and rotor lamination and stator winding are analyzed. Further the performance of the motor is evaluated with temperature influence. In [4] a PV-based deep bore-well submersible pump motor has been designed by using the ferrite magnets and parametric analysis of BLDC

motor like influence of variation of magnet thickness, influence of variation of airgap length, influence of variation of slots/pole/phase have been discussed. This paper follows a analytical design of BLDC Motor for agriculture submersible Pump which is verified with the FEM Analysis.

### A. Agriculture submersible Pump Requirement

The rating of the BLDC motors for agriculture pump application ranges from 188 W to 1.2 kW [3-4], while this paper targets to design a 3.728 kW BLDC motor. The ac motor used in this application does not require any speed control but they should withstand a wide range of voltage fluctuations. Thus, Induction Motors (IM) are best suited for this application domain as they can be started with simple start delta starter, does not require any power electronic drive and less maintenance. But the current IM designs are not energy efficient thus lead to poor energy conservation. It is possible to accomplish low losses by various design optimization techniques, but the associated cost for manufacturing the motor becomes prohibitively high thus making them economically less attractive. This paper aims to achieve a typical agriculture pump Induction Motor torque-speed characteristics in a BLDC motor by considering the test case as in [8] whose performance characteristics is as shown in Fig.1. It can be inferred from Fig. 1 that the IM 3.728 kW capacity has a Starting Torque of 30 N.m with the full load torque of 11 N.m at a rated speed of 2990 RPM which can deliver 3.15 liters per second with a total head of 73.4 meters and the corresponding discharge curve of the pump is shown in Fig.2.

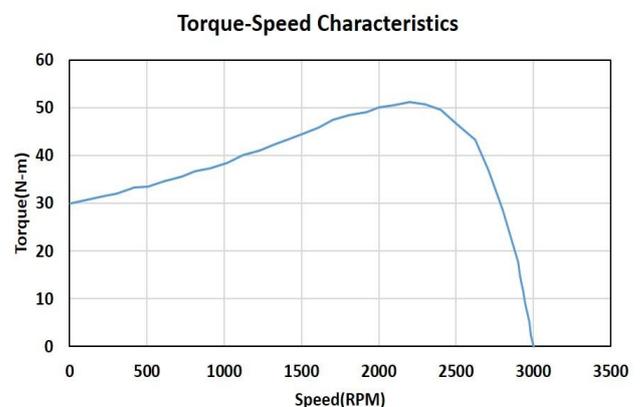


Fig.1 Performance curve of the Induction motor

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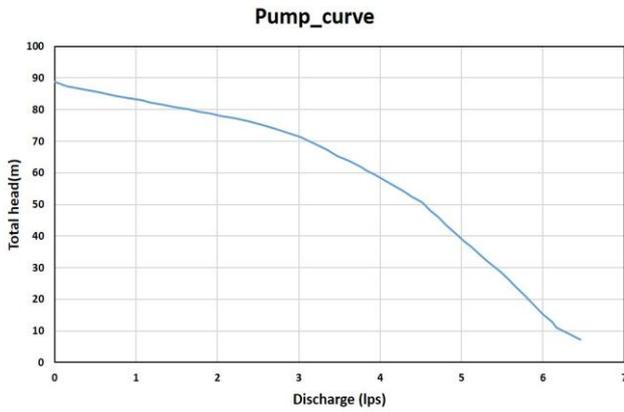


Fig.2 Pump curve of corresponding IM

**B. Analytical Design of BLDC Motor**

BLDC Motor is to be designed to meet the aforementioned specifications. An inner rotor surface mounted type PM motor arrangement produces the highest air gap flux density and requirement does not need high rotational speeds so surface mounted permanent magnet is selected to realize the required BLDC motor. The typical pipe size to be fitted with submersible pumps is around 4 inch i.e., 101.6mm. In order to meet this constraint a 93mm stator outer diameter is chosen with a stack-length  $L_{st}$  of 160mm which is 20mm less than IM [8]. After obtaining the Stack length- $L_{st}$ ,  $D_o$ -Rotor outer diameter can be calculated with the rule of thumb that [6] the rotor outer diameter can be 40% to 65% of the stator outer diameter. Thus a rotor outer diameter  $D_o$  of 58mm is selected, which is accounting to be 62.3% of the stator outer diameter. The next step in the analytical design is obtaining the rotor yoke thickness ( $W_{ry}$ ), stator yoke thickness ( $W_{sy}$ ) and stator teeth thickness ( $W_{tb}$ ). However, for obtaining these parameters it is necessary to have the total number of poles and slots and the next section briefs about the methodology for pole and slot selection.

**1. Pole and slot selection**

Brushless motors can have poles from two to sixty and the most common choices are single digit values [6]. Concurrently, a greater number of poles can result greater torque for a given current. Further, higher number of poles leads to fractional slot windings and selection of lesser number of poles like two poles will be difficult to fabricate and also leads to longer end windings. In order to reduce the core losses it is desirable to use less number of poles for high speed motors. The required speed for the present design being 3000 RPM it is decided to pick 6 poles with a possible slot combination of 18 slots. After the selection of the number of poles and slots the maximum flux density in the Stator yoke and Rotor yoke and stator teeth has to be assumed. For a reasonable design Flux density in stator yoke ( $B_{sy}$ ) and Flux density in rotor yoke ( $B_{ry}$ ) is assumed as 1.2Tesla and Flux density in stator teeth ( $B_t$ ) is assumed as 1.8Tesla[10]. In the next level the rotor yoke, stator yoke and stator teeth thickness are calculated with the standard equations [6] expressed respectively as,

$$W_{sy} = \frac{\pi R_{ro} B_g}{N_m K_{st} B_{sy}} \quad (1)$$

$$W_{ry} = \frac{\pi R_{ro} B_g}{N_m K_{st} B_{ry}} \quad (2)$$

$$W_{tb} = \frac{2\pi R_{ro} B_g}{N_s K_{st} B_t} \quad (3)$$

The Stacking factor- $K_{st}$ , Remenance flux density- $B_r$  and leakage factor- $K_l$  are assumed as 0.9, 1.1 Tesla and 0.956 respectively where  $N_m$  is Number of poles and  $R_{ro}$  is Rotor outer radius and  $N_s$  is Number of Slots. Further the assumption of  $\delta_e$  Equivalent airgap length [10] equal to  $g$  airgap length results airgap flux density  $B_g$  to be equal to 0.725 Tesla. Now using the obtained  $B_g$  value and other constants in equations (1) to (3) the stator and rotor yoke thicknesses and the stator teeth thickness can be obtained thus completing all the geometrical parameters of the required BLDC motor and the so obtained geometry is presented in the Table-1. Next the magnet and type of winding has to be selected for completion of the required design.

Table-I	
Motor Dimensions	
Stator Outer Diameter	93 mm
Stator Inner Diameter	64.8 mm
Axial length of Stator	160 mm
Rotor Outer Diameter	58 mm
Rotor Outer Diameter With Magnet	63.8 mm
Rotor Inner Diameter	39.4 mm

**2. Magnet dimensions**

The type of magnets will have a greater effect on the performance and cost of the motor [7]. The design of magnets includes the inspection of their characteristics so as to retain their operation in the linear region during normal operating ranges at the same time avoiding demagnetization under overload condition. The region of operation of the magnet can be found through the Permeance Coefficient,  $P_c$  as,

$$P_c = \frac{l_m}{g C_\phi} \quad (4)$$

$P_c$  value for ferrite magnets can be greater than 8 [7] and for rare earth magnets its value can be lower. For the present design high energy density rare earth NDFEB magnets are chosen hence permeance coefficient value can be low. With an airgap length  $g$  of 1mm and with the thickness of the magnet  $l_m$  2.4mm and with the flux Concentration factor  $C_\phi$  as 0.8722 we obtain  $P_c$  value as 2.75.

**3. Winding**

The windings are designed in such a way that all the slots are filled; In addition, the number of slots are to be chosen as an integral multiple of the number of phases, thus



$$N_s = kN_{ph} \quad (5)$$

Where,  $N_s$ =No of Slots,  $k$  is a integer and  $N_{ph}$ =No of phases  
For three phase motors the number of slots should be multiples of three and the 18 slots of the present design with all the coils to have the same number of turns will span in same number of slots. This is to obtain same resistance and inductance in each coil. The most common type of winding used in 3-phase radial field permanent magnet machines is (a) Overlapping either distributed or concentrated (b) Non overlapping i.e., concentrated, with either all teeth wound or alternate teeth wound [9]. A two layer distributed winding is decided to be used in the present design with pitch factor ( $K_p$ ) and distribution factor ( $K_d$ ) calculated as,

$$K_p = \cos\left(\frac{\alpha}{2}\right) \quad (6)$$

$$K_d = \frac{\sin\left(\frac{m\beta}{2}\right)}{m\sin\left(\frac{\beta}{2}\right)} \quad (7)$$

Where  $\alpha$  is the difference between coil pitch and pole pitch and  $m$  is the no of slots per pole per phase and  $\beta$  is the slot angle in electrical degrees. When the coil pitch is maintained to be equal to pole pitch the value of  $\alpha$  will be zero and gives  $K_p$  equal to one. Now the distribution factor  $K_d$  and  $K_w$  are calculated as 1. Now the per phase peak back EMF and torque can be calculated from the obtained model as [10],

$$E_b = qn_s K_w \omega_{el} B_{g1} L_{st} (D - g) \quad (8)$$

Where  $q$  - Number of slots per pole per phase.  $n_s$ -Number of conductors per slot. Fundamental Airgap flux density  $B_{g1}$  0.912 Tesla.  $L_{st}$ -Stack length,  $K_w$ -Winding Factor,  $D$ -Inner Diameter of stator,  $g$ -Airgap length,  $\omega_{el}$ -Rotational speed rad/sec. By substituting the values of  $K_w=1$ ,  $n_s=50$  conductors pre slot and the other values in equation (8) the Per phase Peak Back Emf  $E_b$  is obtain as 219.51Volt at  $\omega_m=157.14$  rad/sec. The Torque produced in the machine is expressed as [10]

$$T = \frac{\pi(D - g)^2 L_{st} S_1 B_{g1} K_w \sin(\beta)}{4} \quad (9)$$

Where  $S_1$ - Peak current Loading,  $K_w$  Winding Factor,  $\beta$ - the angle between the current vector and magnet flux vector, which is  $90^\circ$  till the rated torque [10]. From the calculations torque is obtained as 28.49 N.m with  $S_1$  as 61043.03 (Ampere-turns/millimeter) where  $S_1$  is obtained with 13.6 Amperes peak current The other calculated values are given in the table-2 and the Analytically deduced Torque-Speed curve is given in the Fig.3

Table-2			
Motor Details			
S.No	Design parameter	Symbol	Value
1	Per Phase Back EMF	$E_b$	219.51 Volt
2	Back EMF Constant	$K_e$	1.39 Volt.sec/rad
3	Torque	$T$	28.49 N.m

Table-2			
Motor Details			
4	Torque Constant	$T_m$	2.095
5	Winding Factor	$K_w$	1
6	Slot Angle		20 degree
7	No of Slots per Pole Per Phase		1
8	Current Per Phase	$I_{ph}$	13.6 Ampere
9	Pitch Factor	$K_p$	1
10	Resistance per phase	$R_{ph}$	2.68 Ohms
11	Air Gap flux Density	$B_g$	0.725 Tesla
12	Permeance Coefficient	$P_c$	2.751

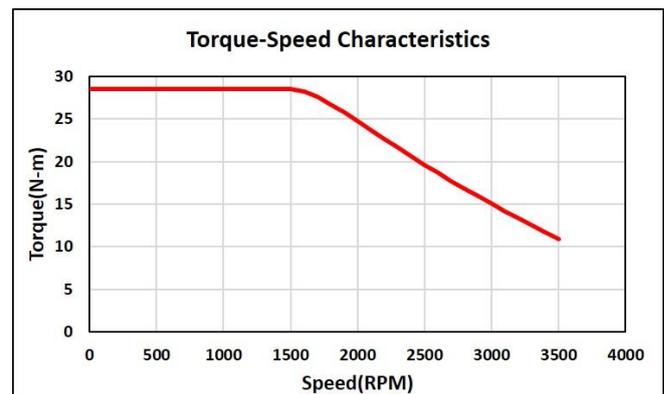


Fig.3 Analytically obtained Torque-Speed curve

## II. FINITE ELEMENT ANALYSIS

FEM Analysis of the designed BLDC motor has been carried out with the parameters of Table 1. For performance prediction of the developed agriculture submersible pump motor. FEMAG Software is used for FEM analysis which is developed at the Institute for Electrical Machines of ETH Zurich in 1982. The 2D model with mesh of the proposed design is shown in the Fig.4. The developed winding model is shown in Fig.5. The materials used in simulation for various parts of the machine are mentioned in Table-3.

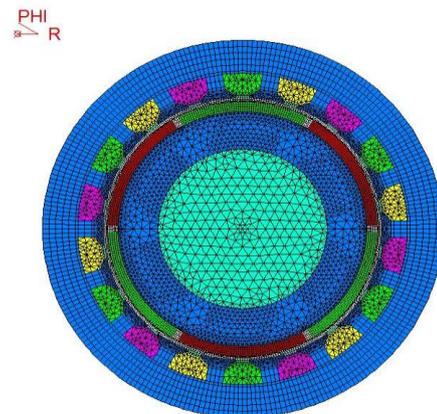


Fig.4 2-D Model with Mesh of Designed Motor

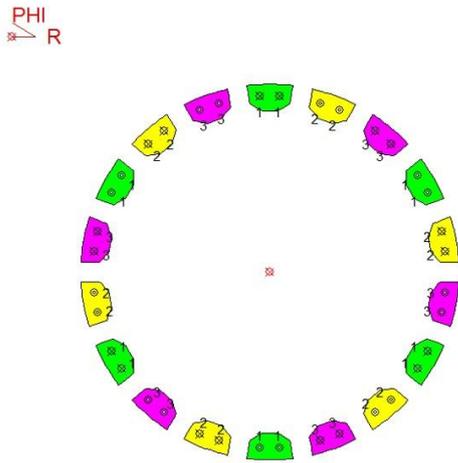


Fig.5 Winding Model of Designed Motor

Table-3	
Materials	
Stator & Rotor	STEEL
Magnets	NDFEB
Winding	COPPER

**A. Results**

To check the air gap flux distribution and the induced voltage a simulation is conducted on the developed BLDC motor under no-load. Comparison to the expected Values allows conclusion of the accuracy of the analytical model. The simulation results of the airgap flux density, Maximum flux density in the stator yoke and stator teeth are compared with the expected values in Table-4. The no-load flux density plot and the no load airgap flux density plot from the simulation results are presented in Fig.6 and Fig.7.

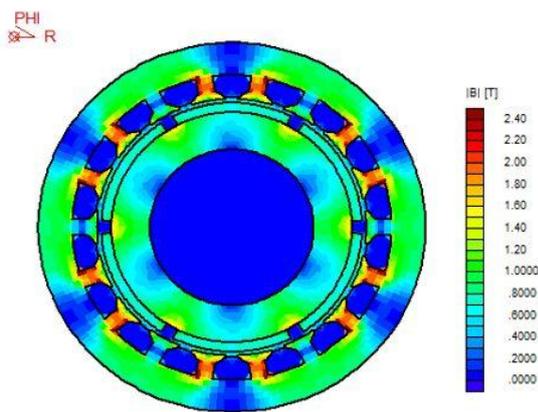


Fig.6 Flux Density plot of 6-pole BLDC Motor

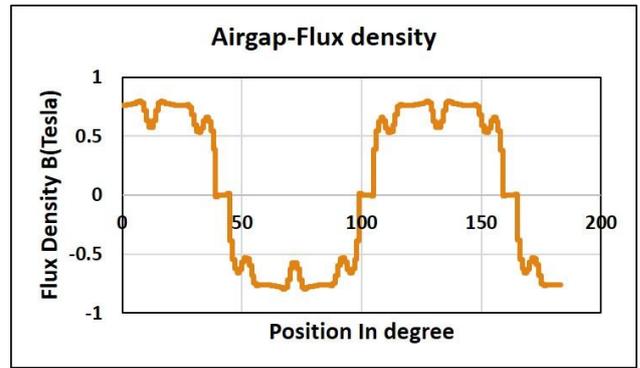


Fig.7 Flux Distribution in Airgap

Table-4		
	Expected Values	FEM Values
$B_g$ (T)	0.72	0.76
$B_{st}$ (T)	1.8	2.3
$B_{sy}$ (T)	1.2	1.3

From Table-4, it can be inferred that the simulation results are slightly deviating from the expected values due to the reason the rotor flux leakage, material non linearity (saturation) and the effect of stator slotting are ignored for the design. The induced back EMF at a speed of 1500RPM is shown Fig.8 and the back EMF values obtained from simulation and the analytical design are presented in Table-5. These two values deviate from each other with 18 percent due to the stator leakage not being considered for the design.

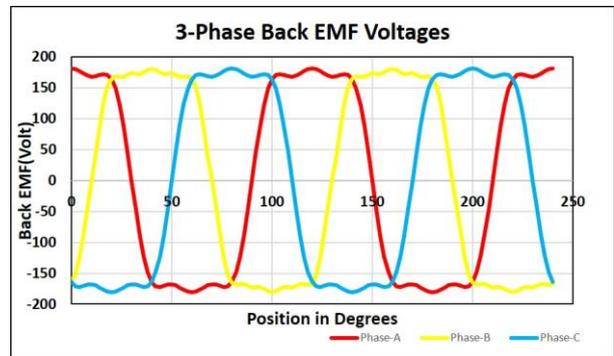
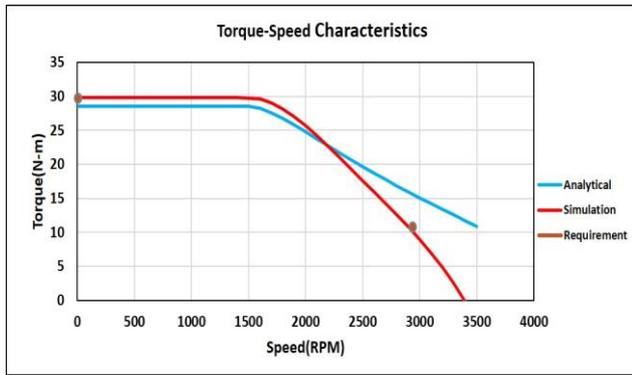


Fig.8 Induced Voltage at 1500rpm

Table-5		
	Analytical Value	FEM Value
$E_b$	219 Volt	181 Volt

Fig.9 shows the Torque-Speed Characteristics Comparison of simulation with analytical for the designed BLDC motor for Agriculture Submersible Pump Application and Simulation result indicates the achievement of the requirement which are specified in the Agriculture submersible pump requirement section.

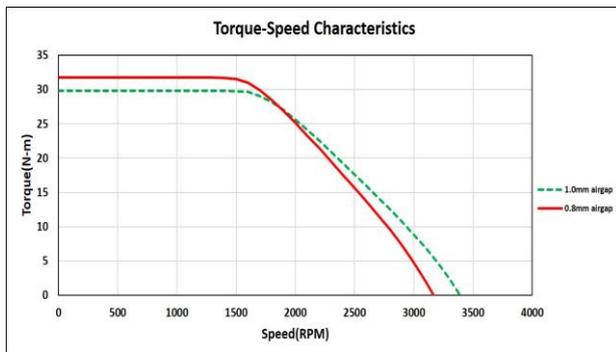


**Fig.9 Comparison of Torque-Speed Characteristics from Simulation with the analytical calculation**

The difference in Torque-Speed Characteristics from analytical to simulation is because stator leakage flux and material Non-linearity (saturation) are not considered in analytical Calculations. Further, the Torque-speed characteristics obtained from FEM analysis for different Air gaps, stack-lengths and magnet widths were presented in Fig. 10 to Fig.12.

• Variation in Airgap (g):

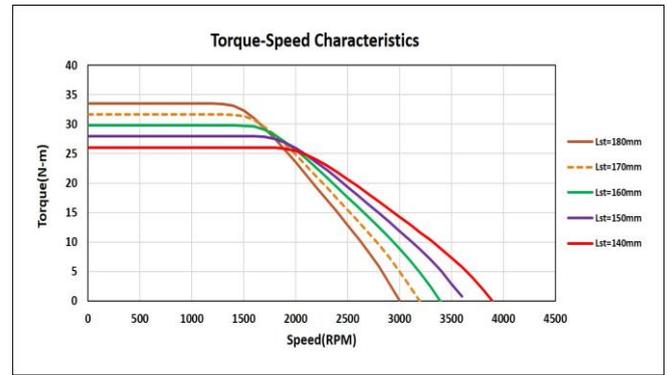
The Torque-Speed characteristics obtained for varying airgap is presented in Fig.10. Variation in airgap leads to change in the starting torque of the motor also the speed in the field weakening region. From Fig.10 it can be noticed that an airgap of 0.8mm results a higher starting torque but with a reduced field weakening region compared to the case with 1.0mm air gap. Thus it is ascertained that if higher starting torques are intended, then machine with lower air gaps are to be suggested but with a tradeoff on the range of field weakening region.



**Fig.10 Torque V/s Speed characteristics for different Airgaps**

• Variation of Stack length ( $L_{st}$ ):

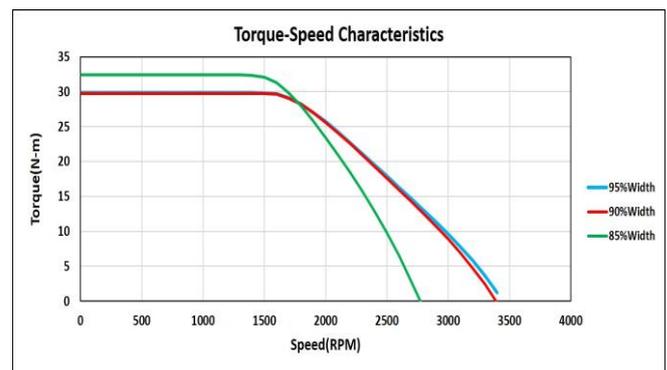
The Torque-Speed characteristics obtained for various Stack lengths is shown in the Fig.11. As stack length increases the starting torque increases as per the relationship expressed in equation (9). The same trend is seen on the field weakening region that higher stack length reduces this region.



**Fig.11 Torque V/s Speed characteristics for different stack lengths.**

• Variation of Magnet Width ( $W_m$ ):

The Torque-Speed Characteristics are obtained for various magnet widths and are shown in Fig.12 from these characteristics it can be inferred that the lower magnet widths will result higher starting torque at the same time a reduction in the Field Weakening region unavoidable. Thus these three geometric parameters viz. Air gap, stack length and magnetic length can be optimized to accomplish a required starting torque and field weakening region as demanded by the application.



**Fig.12 Torque V/s Speed characteristics for different Magnet Widths**

**III. CONCLUSIONS**

In this paper, the design of a surface mounted BLDC Motor for Agriculture submersible pump application has been obtained. The design process requires a variety of considerations. The obtained design is further verified with the FEM Analysis software FEMAG. Comparison between analytical and simulation for Back EMF, torque-speed characteristics and flux densities in Stator, Rotor and Airgap are presented. Based on analytical models and finite element analysis, 3-phase 18slot 6 pole BLDC motor for agriculture pump is designed. Also influence of various parameters like Airgap, Stack length and width of the magnet parameters are studied using FEM analysis.

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