Brushless DC Motor Design for Electric Traction System

Md. Bashir Sheikh
Priyadarshini Institute of Engineering & Technology

Priti. S. Manware
Priyadarshini Indira Gandhi College of Engineering

Abstract

BLDC motor is the permanent magnet synchronous motor designed to have a trapezoidal back emf. Due to rugged construction, less control complexity, higher power density, variable speed over a wide range and flexibility to select the rotor construction suitable for particular application, it is being viewed as an alternative for conventional a.c. motors right from residential to commercial & aerospace systems. Rotation of BLDC motor is achieved by energizing the stator phases in a sequence, which depends on the rotor position. Hall sensors are used to detect the exact position of the rotor. This paper presents design of BLDC motor drive. For the purpose of demonstration, the popularly used loads are considered for industrial application, electric traction system.

Keywords: Brushless DC (BLDC) motor, electric traction system

I. INTRODUCTION

BLDC motor is simple and rugged when compared with d.c. and induction machine. It is same as that of 3 phase a.c. machine but only two phases are excited at a time. Now a days BLDC motor is preferred as compared to brushed DC motor due to higher reliability, efficiency and lower noise. This is observed in every field such as in residential, industrial, automotive and household applications, because of high torque, lower maintenance and variable speed control [1]-[3]. The advantages of BLDC motor over brushed DC motor are presented below.

- Armature winding on the stator makes it easy to conduct heat away from the winding.
- High speed, high power to size ratio, and no arcing on commutation.
- Low inertia and higher acceleration.

BLDC motor is more efficient than brushed d.c. motor because of the absence of friction due to brushes. It consists of 3 phase stator winding, permanent magnet rotor and an electronic controller having inverter and converter. Input a.c. power is fed to the stator winding through the inverter switches as per desired phase sequence. Rotor rotates in the direction based on switching sequence of the inverter [4], [5]. Position of the rotor is sensed by Hall Effect sensor. Three sensors are displaced from each other by 120^0 electrical and are mounted on the shaft of the rotor. When the rotor magnetic poles pass near the hall sensors, they supply a high or low signal that indicates north or south poles. Based on combination of these

Three hall sensor signals, the exact sequence of commutation can be determined.

II. CRITERION FOR SELECTION OF MOTOR

For selection of reliable and efficient motor it is essential that the conditions of service are known. It is not sufficient to specify the output power in kW and speed, but it is also necessary to know the following information.

- Torque at the shaft during running, starting and at different loads.
- Accelerating torque and braking torque.
- Switching frequency.
- Efficiency of motor at different load.
- Other working requirements.

In studying the behavior of a motor selected for a particular driven unit, one of criterion is to determine whether the speed torque characteristic of motor suits the requirement imposed by the speed torque characteristic of the driven unit. Drive behavior during the transient period of a startup, braking or speed changeover also depends upon how the speed torque characteristics of motor and the driven unit vary with speed. Therefore it is important to study speed-torque characteristic to select correct motor and obtain an economical drive.

A. Speed-Torque Characteristics of the Motor-Load Mechanisms:

The speed torque characteristics of a motor is given by the relation $\omega = f(T_L)$. It is defined as relationship between the speed at which it is operated and the load torque. Speed torque characteristics of different kinds of load are divided into the following categories.

1) Load with Constant torque at all speeds: This kind of load offers passive torque to the motor which is essentially independent of the speed. Examples of such load are dry friction, cranes during hoisting, hoist winches, piston pumps operating against a constant pressure head and conveyors.
2) Load with linear- rising characteristics: In this type of load the load torque T_L rises in direct proportion to the speed. Popular example is calendaring machine.
3) Load with non- linear rising (Parabola) characteristic: In this type of load, the load torque T_L is proportional to the square of the speed. Windage torque is the dominating component of this load. Different examples are Fan, Blowers, Centrifugal pumps, Propellers in ships or aeroplanes, water wheels, etc.
4) Load with non- linear falling (Hyperbolic) characteristic: For such type of load, the torque T_L is inversely proportional to the speed while power required to drive the given unit remains unchanged. Certain types of lathe, boring machine, milling machine and other kinds of metal cutting machine, steel mill coilers fall under this category of loads.
5) Traction loads: These are the high torque loads which may vary continuously depending upon speed, time and the path or position of the vehicle during motion. The stiction and windage torques play dominating roles during starting and running conditions respectively. The performance during acceleration, free-running, costing and deceleration is of importance in this type of load (Fig. 1). Popular examples are: railway traction, electric vehicle etc.

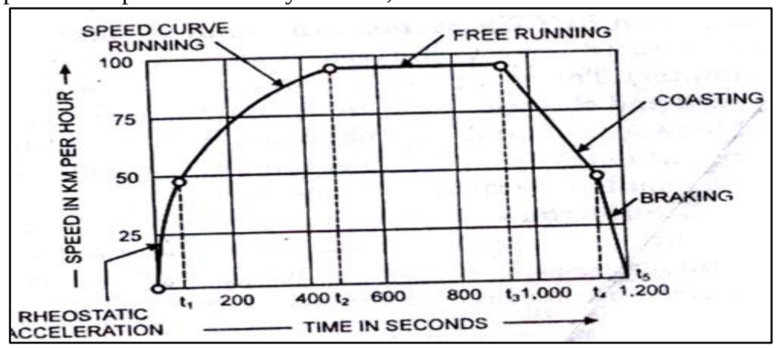

Fig. 1: Speed –time curve of a typical traction load.

B. *Load -Torque Variation versus Time Characteristics for Different types of Load:*

Variation of load-torque with time is of equal or greater importance in selection of motor. This variation in certain applications can be periodic and repetitive. One cycle of variation is called a duty cycle. Different types of load having different load characteristics are classified as follows.

1) Continuous constant load: These loads operate for a long time under the same condition. Examples are paper making machine, centrifugal pumps, etc.
2) Continuous variable load: Hoisting winches, metal cutting lathes, conveyors are the examples of continuous variable type load.
3) Pulsating load: Reciprocating pump, textile looms and all machines having crank shaft come under this type of load.
4) Short- time load: Examples are motor generator set for charging of batteries, servo motors used in remote control of drilling machine and clamping rods.
5) Short-time intermittent load: Crane and hoisting mechanism, excavators, and roll train are examples of this type of load.

III. DESIGN OF BLDC MOTOR FOR ELECTRIC TRACTION SYSTEM

In electric vehicles, the prediction of vehicle propulsion in accordance with power characteristics and torque requirements of the vehicle is the key component for the design of an appropriate traction motor because the speed-torque characteristics of the traction motor completely determines the vehicle performance [8]-[11]. The parameters of vehicle load used for the design of BLDC motor are presented in Table I. [12].

Table – 1
Parameters of Vehicle Load

Symbol	*QUANTITY*	*Description*
M	*200 tonne*	*Weight of vehicle*
D	*0.9 m*	*Diameter of driving wheel*
G	*3%*	*Percentage-gradient*
R	*50 N/tonne*	*Tractive resistance*
Γ	*4*	*Gear ratio*
H	*90%*	*Gear transmission efficiency*
A	*2.015*	*Acceleration*

m= meter, N = Newton, %= percentage

A. *Torque Required Propelling the Vehicle:*

THE TRACTIVE FORCE NECESSARY TO PROPEL THE VEHICLE AT THE WHEELS IS GIVEN BY

$$F_t = Fa + F_g + F_r \ \ (N) \qquad (17)$$

Where, the force required for giving linear acceleration is,

$$F_a = 277.8\ \alpha\ M_e \ \ (N) \qquad (18)$$

The force required to overcome the gravitational effect is,

$$F_g = 98MG\ (N) \qquad (19)$$

And the force required to overcome resistance to the motion is,

$$F_r = M\ r\ (N) \qquad (20)$$

The torque required to propel the vehicle is given by,

$$T = F_t\ D\ /\eta\ 2\gamma \ \ \ (Nm) \qquad (21)$$

Where D is diameter of the wheel, η is gear efficiency and γ is the gear ratio.

Substitution of parameter values in (17)-(21) gives,

$F_t =$ 192000 N

T = 24000 Nm

Assuming four numbers of motors, therefore torque required to be developed by each motor will be

T = 6000 Nm

B. *Selection of the type of BLDC Motor for Vehicle Load:*

The construction of BLDC motor is broadly classified into two topologies i.e. radial flux type and axial flux type. The radial flux BLDC motor also called as cylindrical type motor is further classified into outer stator type and outer rotor type. This motor is further categorized as surface mounted type and interior permanent magnet type [13]. The axial flux BLDC motor also called as pancake type motor is classified as single air-gap type and dual air-gap type.

The radial flux construction is suitable for low power density applications. It is known that force generated in a motor is a function of the product of flux density in the core and the slot current. In a radial flux construction, if the current is to be increased, more slot area is required to maintain constant resistive loss and the maximum air-gap flux density decreases and vice-versa. Thus if electric loading gets too high, the magnetic loading must decrease.

The electric vehicle application requires high power density of the motor which is possible with dual air-gap type axial-flux construction [2], [14]. The schematic diagrams of single air-gap and dual air-gap type pancake motors are shown in Fig. 2 (a) & (b). The detail design of a dual air-gap type BLDC motor for vehicle load having parameters given in Table.1 is presented in this paper. Some authors in the literature have suugested the use Spoke type BLDC motor for traction applications [15].

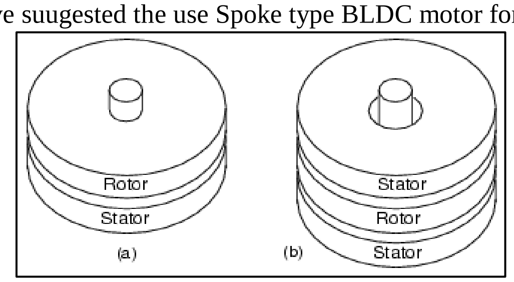

Fig. 2: Axial Flux BLDC Motor (a) single air-gap type, (b) dual air-gap type

C. *Design of Dual Air-Gap type BLDC Motor:*

The fixed parameters for the motor are calculated from the vehicle parameters (given above). They are presented in Table II.

Table – 2
Fixed Parameter for Motor Design

Symbol	***Quantity***	***Description***
Sr	***1179 rpm***	***Motor Speed***
T	***6000Nm***	***Required torque***
Ri	***0.15m***	***Inside radius***
Ro	***0.45m***	***Outside radius***
N_S	***24***	***No. of Slot***
N_{ph}	***3***	***No of phases***
N_m	***4***	***No. of Magnet pole***

m= meter, rpm = revolution per minute; N-m = Newton meter

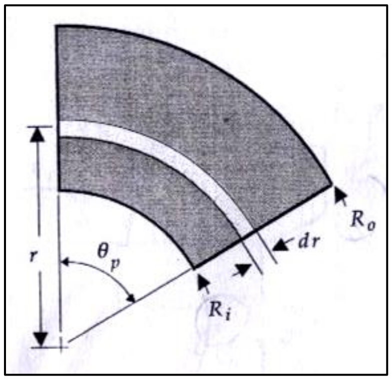

Fig.3. Geometry of motor radius

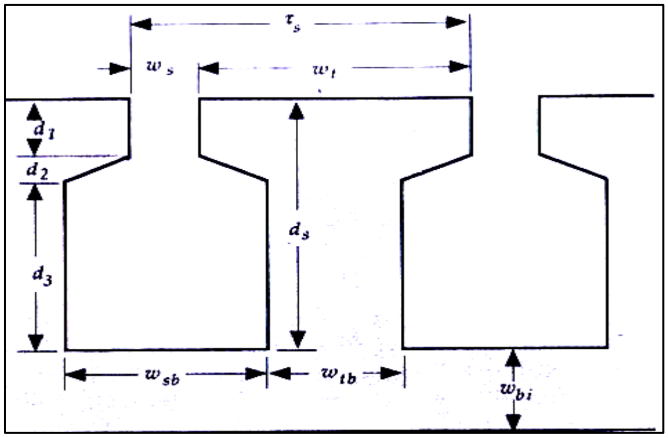

Fig.4. Geometry Slot for dual axial flux motor

When a slotted stator design is chosen there are many combinations of slots, poles, windings, and phases allow to acceptable motor design. For stator design there is no of stator slot N_s [2].

$$N_s = N_{sp}\, N_{pH} = 8 * 3 = 24 \quad (24)$$

Where, number of slots per phase N_{sp} is 8 and is number of phases N_{ph} is 3.
Number of slot per pole per phase N_{spp} is,

$$N_{spp} = \frac{N_{sp}}{N_m} = 2 \quad (25)$$

N_m is number of magnet poles on the rotor.
A_g is the air gap cross- sectional area given by,

$$A_g = \frac{\pi(1+\alpha_m)}{2N_m}(R_o^2 - R_i^2) = 0.217\text{m}^2 \quad (26)$$

Where the magnet fraction $\alpha_m = 0.86$
The air gap flux Φ_g is,

$$\emptyset_g = B_g A_g = 0.9 * 0.217 = 0.117 \text{ Wb} \quad (27)$$

Where, B_g is the air gap flux density.
Back iron width W_{bi} is given by,

$$W_{bi} = \frac{B_g \tau_{po}}{2B_{max} k_{st}} = 0.323\text{m} \quad (28)$$

Where B_{max} is the maximum allowable flux density in the back iron and B_g is the air gap flux density .The outside pole pitch τ_{po} = 0.706m and stacking factor $k_{st} = 0.9$.
The inner radius Wtbi is

$$W_{tbi} = \frac{B_g \tau_{pi}}{N_{sm} B_{max} k_{st}} = 0.036\text{m} \quad (29)$$

Where the inside pole pitch τ_{pi} = 0.2355m.
Slot bottom width W_{sb} is,

$$W_{sb} = \tau_{si} - W_{tbi} = 0.003\text{m} \quad (30)$$

Where, inside slot pitch τ_{si} = 0.0391m.
The number of turns per slot n_s is equal to

$$n_s = \left(\frac{E_{max}}{N_m k_d k_p k_s B_g N_{spp}(R_0^2 - R_i^2)\omega_m}\right) = 5 \text{ turn/slot} \quad (31)$$

Where, K_d is distribution factor 0.9.
Peak slot current I is given by

$$I_s = \frac{T}{N_m k_d k_p k_s B_g N_{spp}(R_0^2 - R_i^2)} = 6806.97A \qquad (32)$$

I_{ph} is phase current under the assumption that all phases contribute equally and simultaneously to the motor. If all phases N_{ph} are conducting current simultaneously and back emf wave is square wave then phase current is

$$I_{ph} = \frac{I_s}{N_{ph} n_s} = 453.79 \text{ Amp} \qquad (33)$$

IV. CONCLUSION

In this paper, a detailed study of BLDC motor design for Electric vehicle load for industrial application. Motor is designed for special application that is electric traction system.. Design result proves the feasibility of this motor drive for industrial load. The inherent advantages of BLDC motor drive related with variable speed, high efficiency, low maintains and high speed range are extended to this load. In future, it is expected that BLDC motor will replace the conventional induction motor in many domestic & industrial applications.

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