International Journal of Electrical, Electronics and Computer Engineering **4**(1): 114-119(2015)

ISSN No. (Online): 2277-2626

Selection & Design of BLDC Motor for Different Applications

Priti S. Manware*, Md. Bashir Sheikh** and M.R. Shelke*

**Assistant Professor, Department of Electrical Engineering, PIGCOE, Nagpur, (MS), India,*

***Assistant Professor, Department of Electrical Engineering, PIET, Nagpur, (MS), India,*

(Corresponding author: M.R. Shelke)

(Received 04 February, 2015 Accepted 24 March, 2015)

(Published by Research Trend, Website: www.researchtrend.net)

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 the review, modeling, design & simulation of BLDC motor drive. For the purpose of demonstration, the popularly used loads are considered. Residential application is studied with fan type load whereas for industrial application, electric vehicle is considered. The simulation is carried out in MATLAB/ Simulink environment.

Keywords: Brushless DC (BLDC) motor, Hall effect sensor, electric vehicle, fan.

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.

(i) Armature winding on the stator makes it easy to conduct heat away from the winding.

(ii) High speed, high power to size ratio, and no arcing on commutation.

(iii) 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. MODELING OF BLDC MOTOR

To derive the model of BLDC motor, following assumptions are made [6], [7].

(i) Currents in rotor due stator harmonic field are neglected.

(ii) Iron and stray losses are neglected and damping is provided by inverter control.

The per phase voltage relation for stator side is:

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} + \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} p \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_{as} \\ e_{bs} \\ e_{cs} \end{bmatrix} \quad (1)$$

where, R_s is stator resistance/ phase, and e_{as}, e_{bs}, e_{cs} are the induced emfs assumed to be trapezoidal. The emf induced/conductor is given as,

$$e = (Blv)\,N \quad (2)$$

$$e = N\,(B\,l\,r\,\omega_m) \quad (3)$$

$$e = N\,\phi\,\omega_m$$

$$e = \lambda_p\,\omega_m \text{ volt} \quad (4)$$

where, N is the number of conductor in series/phase, v is the velocity in (m/s), l is the length of the conductor in (m), r is the radius of rotor bore in (m), ω_m is the angular velocity in (rad/s), B is flux density of the field in (wb/m^2), in which the conductors are placed. The product of (Blr) denoted as ϕ and λ_p is the flux linkage in (V.s). There is no change in the rotor reluctance with angle because of non-salient rotor. Assuming three symmetric phases, self induced emf in the three phases are $L_{aa} = L_{bb} = L_{cc} = L$ and mutual inductances are $L_{ab} = L_{ba} = L_{ca} = L_{bc} = L_{cb} = M$. Substituting these value of inductance in (1).

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} = R_s \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} + \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & o \\ 0 & 0 & L-M \end{bmatrix} p \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_{as} \\ e_{bs} \\ e_{cs} \end{bmatrix} \qquad (5)$$

The electromagnetic torque is, $T_e = [e_{as}\, i_{as} + e_{bs}\, i_{bs} + e_{cs}\, i_{cs}\,]\frac{1}{\omega_m}$ (N.m) (6)

The instantaneous induced emf can be written as

$$e_{as} = f_{as}(\theta_r)\lambda_p\omega_m \qquad (7)$$

Where,

$$T_e = \lambda_p[f_{as}(\theta_r)i_{as} + f_{bs}(\theta_r)i_{bs} + f_{cs}(\theta_r)i_{cs}\,] \;\text{(N.m)} \qquad (8)$$

The equation of motion for a simple system with inertia *J*, friction coefficient *B* and load torque T_l is,

$$J\left(\frac{d\omega_m}{dt}\right) + B\omega_m = T_e - T_l \qquad (9)$$

The relation between electrical rotor speed and rotor position is

$$\frac{d\theta_r}{dt} = \frac{p}{2}\omega_m \qquad (10)$$

In (5), substitute $L_1 = L - M$, the current equations in state space form are obtained as,

$$pi_{as} = \frac{1}{L1}[-R_s\ \ i_{as} - e_{as}] + \frac{v_{as}}{L1} \qquad (11)$$

$$pi_{bs} = \frac{1}{L1}[-R_s\ \ i_{bs} - e_{bs}] + \frac{v_{bs}}{L1} \qquad (12)$$

$$pi_{cs} = \frac{1}{L1}[-R_s\ \ i_{cs} - e_{cs}] + \frac{v_{cs}}{L1} \qquad (13)$$

From (8) & (9),

$$J\frac{d\omega_m}{dt} + B_m\omega_m + T_l = \lambda p[f_{as}(\theta_r)i_{as} + f_{bs}(\theta_r)i_{bs} + f_{cs}(\theta_r)i_{cs}]$$

$$\frac{d\omega\,m}{dt} = \frac{F_{as}(\Theta_r)\,i_{as}\lambda_p}{J} + \frac{F_{bs}(\Theta_r)\,i_{bs}\lambda_p}{J} + \frac{F_{cs}(\Theta_r)\,i_{cs}\lambda_p}{J} - \frac{Bm\,\omega m}{J} - \frac{Tl}{J}$$

$$p\omega_m = \frac{F_{as}(\Theta_r)\,i_{as}\lambda_p}{J} + \frac{F_{bs}(\Theta_r)\,i_{bs}\lambda_p}{J} + \frac{F_{cs}(\Theta_r)\,i_{cs}\lambda_p}{J} - \frac{Bm\,\omega_m}{J} - \frac{Tl}{J} \qquad (14)$$

Expressing the above relations in state space as

$$px = \mathbf{A}x + \mathbf{B}u \qquad (15)$$

where $x = [i_{as}\ i_{bs}\ i_{cs}\ \omega_m\ \theta_r]^t$ and $u = [v_{as}\ v_{bs}\ v_{cs}\ T_l]^t$

$$A = \begin{bmatrix} -\frac{R_s}{L_1} & 0 & 0 & -\frac{\lambda_p}{L_1}f_{as(\theta_r)} & 0 \\ 0 & -\frac{R_s}{L_1} & 0 & -\frac{\lambda_p}{L_1}f_{bs(\theta_r)} & 0 \\ 0 & 0 & -\frac{R_s}{L_1} & -\frac{\lambda_p}{L_1}f_{cs(\theta_r)} & 0 \\ \frac{\lambda_p}{J}f_{as(\theta_r)} & \frac{\lambda_p}{J}f_{bs(\theta_r)} & \frac{\lambda_p}{J}f_{cs(\theta_r)} & \frac{-B}{J} & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} \frac{1}{L_1} & 0 & 0 & 0 \\ 0 & \frac{1}{L_1} & 0 & 0 \\ 0 & 0 & \frac{1}{L_1} & 0 \\ 0 & 0 & 0 & \frac{-1}{J} \\ 0 & 0 & 0 & 0 \end{bmatrix} \qquad (16)$$

Eq. (16) represents the dynamic model of a non-salient rotor type BLDC motor.

III. 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.

(i) Torque at the shaft during running, starting and at different loads.
(ii) Accelerating torque and braking torque.
(iii) Switching frequency.
(iv) Efficiency of motor at different load.
(v) 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 start up, 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.

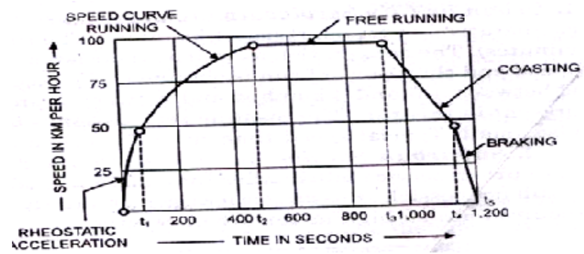

Fig. 1. Speed–time curve of a typical traction load.

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 machine 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, roll train are examples of this type of load.

IV. DESIGN OF BLDC MOTOR FOR ELECTRIC VEHICLE

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 1. [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 to propel the vehicle

The tractive force necessary to propel the vehicle at the wheels is given by

$F_t = F_a + F_g + F_r$ (N) (17)

Where, the force required for giving linear acceleration is,

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

The force required to overcome the gravitational effect is,

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

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

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

The torque required to propel the vehicle is given by,

$T = F_t\,D\,/\eta\,2\gamma$ (Nm) (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 number 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].

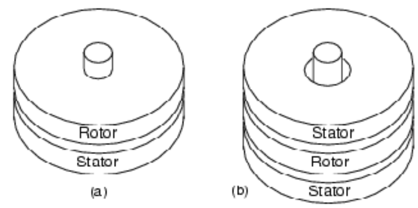

Fig. 2. Axial Flux BLDC Motor (a) single air-gap type, (b) dual air-gap type.

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 2.

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

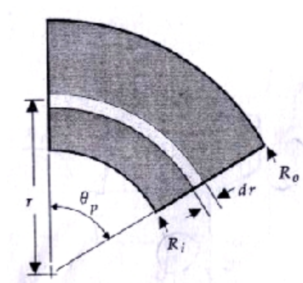

Fig. 3. Geometry of motor radius.

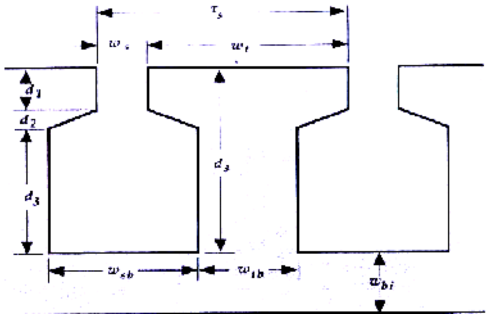

Fig. 4. Geometry Slot for dual axial flux motor.

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,

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

Where the magnet fraction α_m = 0.86

The air gap flux Φ_g is,

$$\Phi_g = B_g A_g = 0.9 \times 0.217 = 0.117\, Wb \quad (27)$$

Where, B_g is the air gap flux density.

Back iron width W_{bi} is given by,

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

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 W_{tbi} is

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

Where the inside pole pitch τ_{pi} = 0.2355m.

Slot bottom width W_{sb} is,

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

Where, inside slot pitch τ_{si} = 0.0391m.

The number of turns per slot n_s is equal to

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

Where, K_d is distribution factor 0.9.

Peak slot current I_s is given by

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

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

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

V. BLDC MOTOR FOR RESIDENTIAL APPLICATION: FAN TYPE LOAD

The radial flux type BLDC motor is of two types. One is rotor inside stator and another is rotor outside of stator. For fan type application, rotor outside stator construction is preferred. Conventional ceiling fan uses induction motor which comparatively has larger size. Induction motor usually operates at high slip due to which performance of ceiling fan is poor. BLDC motor is advantageous for fan type application because the energy consumption of BLDC motor is less as compared to induction motor. Also, relatively the noise produced is less [8]-[11]. In fan, the windage dominates consequently, load torque is proportional to speed squared. The speed torque relation for fan type load is [12],

$$T_l = K\omega_m^2 \quad (34)$$

The power developed at motor shaft is given by,

$$P = K\omega_m^3 \quad (35)$$

This load is unidirectional. It is required to run at constant speed for a longer time or at several speed settings or over range of speed. A general scheme of BLDC motor drive is shown in Fig 5.

The 3-phase AC input is first rectified and then converted to variable voltage, variable frequency AC by using 3-phase inverter. Output of the inverter is fed to the stator winding. Based upon the rotor position identified by Hall Effect sensor, the controller generates appropriate switching pulses for the inverter so as to equalize the actual speed with reference speed under different operating condition.

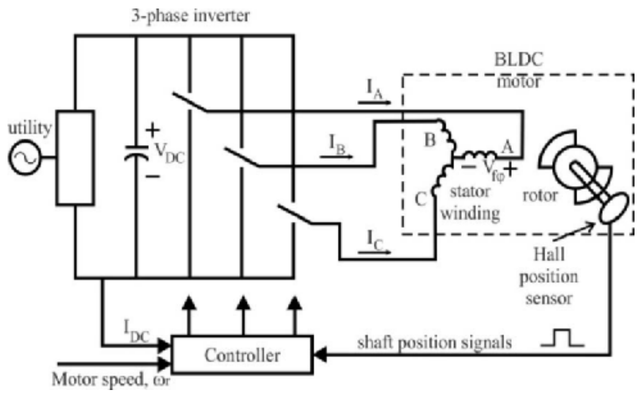

Fig. 5. BLDC motor drive.

VI. CONCLUSION

In this paper, a detailed study of BLDC motor design for Electric vehicle load for industrial application and BLDC motor drive feeding fan type load for residential application is presented. Motor is designed for special application that is electric vehicle also motor dynamic model is derived and simulation study is carried out in MATLAB/Simulink environment under four different operating conditions. Design and simulation result proves the feasibility of this motor drive for both industrial and residential 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.

REFERENCES

[1]. R. Krishnan, *Electric Motor Drives: Modeling, Analysis and Control*, Prentice Hall, 2001.

[2]. D. Hanselman, *Brushless Permanent Magnet Motor Design,* McGraw-Hill.

[3]. P.C. Krause, O. Wasynczuk , *Analysis of Electric Machinery and Drive Systems,* Wiley India.

[4]. S. Prakashand, R. Dhanasekaramm" Modelling and simulation of closed loop controlled buck converter fedpmbldc drive system" *Research Journal of Applied Science, Engineering and Technology* **3**(4): 284-289, 2011.

[5]. Vandana Govindan T.K , Anish Gopinath, "DSP based Speed Control of Permanent Magnet Brushless DC Motor", *IJCA Special Issue on "Computational Science - New Dimensions & Perspectives"* NCCSE, 2011.

[6]. De,S., Rajne, M., Poosapati, S., Patel, C., Gopakumar, K. "Low inductance axial flux BLDC motor drive for more electric aircraft" *IEEE Aerospace conference -2011.*

[7]. Yong-Han Kim, Bo-Suk Yang , Chang-Joon Kim, "Noise Source Identification of Fan- Small BLDC Motor System for Refrigerators", *International Journal of Rotating Machinery* Volume 2006, Article ID 63214, pp 1–7.

[8]. J.B. Gupta, *Utilization of Electric Power & Electric Traction,* S. K. Kataria & Sons, pp 411- 480.

[9]. Jinsong Kang, Guoqing Xu," Research on Field-Weakening Based on Reactive Power with BLDC Motor for Electric Vehicle Application" *IEEE International Conference on Integration Technology March 20-24, 2007, Shenzhen, China Proceedings 2007*.

[10]. David Dorrell, Mircea Popescu, "Analysis and Design Techniques Applied to Hybrid Vehicle Drive Machines—Assessment of Alternative IPM and Induction Motor Topologies". *IEEE Trans on Ind. Electronics*, Vol **59**, No. 10, Oct 2012.

[11]. Nam-Hun Kim, Oh Yang, Min-Huei Kim, "BLDC Motor Control Algorithm for Industrial Applications Using a General Purpose Processor". *Journal of Power Electronics*, Vol. **7**, No. 2, April 2007.

[12]. Y. Kim, Se. Rhyu, "Parameter determination of BLDC motor considering the dynamic equation of Vehicle", *XIXI International conference on Electrical machine, ICEM 2010,* Rome.

[13]. Gianmario Pellegrino, Paolo Guglielmi, Barbara zzo, "Performance Comparison Between Surface-Mounted and Interior PM Motor Drives for Electric Vehicle Application'', *IEEE Transactions on Industrial Electronics*, vol. **59**, no. 2, February 2012.

[14]. Su-Beom Park, Ji, Young, "Characteristic analysis of the Axial-Flux Type Brushless DC Motor Using Image method", *15th COMPUMAG Conference on the computation of Electromagnetic Field,* June 2005.

[15]. B. Lee, G. Kang, " Design of spoke type BLDC motor with high power density for traction application,*7803-8486 – 5/4/2004 IEEE.*