Design a single-phase BLDC Motor and Finite-Element Analysis of Stator Slots Structure Effects on the Efficiency

Abdolamir Nekoubin

***Abstract*—**In this paper effect of stator slots structure and switching angle on a cylindrical single-phase brushless direct current motor (BLDC) is analyzed. BLDC motor with three different structures for stator slots is designed by using RMxprt software and efficiency of BLDC motor for different structures in full-load condition has been presented. Then the BLDC motor in different conditions by using Maxwell 3D software is designed and with finite element method is analyzed electromagnetically. At the end with the use of MATLAB software influence of switching angle on motor performance investigated and optimal angle has been determined. The results indicate that with correct choosing of stator slots structure and switching angle, maximum efficiency can be found.

***Keywords*—**Permanent magnets, Switching angle, BLDC motor

I. Introduction

Conventional DC motors are highly efficient, however, their only drawback is that they need a commutator and brushes which are subject to wear and require maintenance. The above mentioned deficiency of the conventional solution can be overcome by the new type of DC drive based on brushless DC motors operating without mechanical transmission [1]. The brushless DC motors (Fig. 1) are permanent magnet motors where the functions of commutator and brushes were implemented by solid state switches [2]. The brushless DC motors are distinguished not only by the high efficiency but also by their no maintenance.

As far as rotary motor geometry is concerned two types of structures are met:

Cylindrical and disc structure, According to [3] the topologies of cylindrical motors may be classified as follows:

1. Cylindrical motor with internal rotor
2. Cylindrical motor with external rotor

Recently, brushless DC motors have been widely used in large-scale industry applications such as automotive, aerospace, home appliances and many industrial equipment and instrumentation for various applications [4], [5]. The construction of modern BLCD motors is very similar to the ac motor, known as the permanent magnet synchronous motor. BLDC motors come in single-phase [6], two-phase and three-phase configurations [7]. The stator of a BLDC motor consists of stacked steel laminations with windings placed in the slots that are axially cut along the inner periphery or around stator salient poles. The rotor is made of permanent magnets and can vary from two to eight pole pairs with alternate north (N) and south (S) poles. Based on the required magnetic field density in the rotor, the proper magnetic material is chosen to make the rotor. Ferrite magnets are traditionally used to make permanent magnets. As technology advances, rare earth alloy magnets are gaining popularity. In order to make a BLDC motor rotate, the stator windings should be energized in a sequence. It is essential to know the rotor position in order to understanding as to which winding must be energized [8]. The magnetic flux generated by the current in the stator winding can increase or decrease the flux density in the stator depending on the rotor position, leading to decrease or increase in inductance due to the saturation of the stator. By applying positive and negative voltage pulses consecutively and measuring the difference in inductance, it can be indicated which magnetic polarity the phase winding is facing [9].

Consecutively and measuring the difference in inductance, it can be indicated which magnetic polarity the phase winding is facing. As electromagnetic forces result from the interaction between the rotor and the stator through the magnetic field in the air-gap space in between, an accurate prediction of the instantaneous magnetic fields is essential. When designing electrical motors, both the analytical and numerical methods, e.g., finite-element methods (FEM) are used frequently. Even as FEM is well suited for failure analysis and design validation purposes, analytical methods are useful as efficient tools for quick evaluation of the motor performance with given settings of design parameters. Thus, developments of effective analytical approaches for BLDC motor design syntheses continue to attract great attention from researchers, e.g., [10]. The synthesized procedure to achieve the flux density distribution for special motor with the help of numerical methods has been widely used [11]. For instance, it can be used to estimate the back electromotive force (EMF) and the inductance of the stator windings [12], the frequency spectra of the magnetic induced forces which signify the magnetically induced vibration sources [13]-[14], the running torque, and some other aspects of the permanent magnet (PM) motor performances [15], [16]. In [17], is presented the computational method for analyzing a BLDC motor taking into consideration the freewheeling diodes and dc link voltage ripples using a time-stepped finite element method. The results show that the proposed analysis method is suitable for analyzing a BLDC motor by comparing the predicted and the measured phase currents and dc link voltage ripples with

Abdolamir Nekoubin is with the Electrical Engineering Department, Islamic Azad University Najaf Abad Branch (e-mail: nekoubin@yahoo.com).

experimental data.

In [18], a new structure of brushless DC motor with passive magnetic bearings is introduced. The magnetic suspension of the rotor is realized by using the proposed passive magnetic bearings and does not need to be controlled. The axial stability of the rotor can be obtained by the radial force of the passive magnetic bearings and by the instinctive behavior of the PM motor in axial alignment of the stator and rotor. The radial magnetic suspension of the machine rotor can be realized by the optimal design of the air-gap length, thickness and axial length of the PM rings both of the passive magnetic bearings and the BLDC motor based on the accurate calculation of radial and axial forces. A new type of PMSM with Opposite-rotation Dual rotors (ODR) has been proposed to improve operation performance of underwater vehicle (UV) propulsion system. Comparing to two main driving modes (double rotors DC motor and conventional motor with planetary gears), the system performance improve greatly due to the remove of brush, commutator and gears. Furthermore, because of rare earth magnets used in this machine, the efficiency and torque density has been improved. The ODR machine can provide two independent opposite torques with single power supply due to special structure, so it can drive counter-rotation propeller directly [19].

The objective of the paper is to analyze the performance and efficiency of the BLDC motor (cylindrical type with internal rotor), stator coils of the motor can be connected in single-phase or poly-phase systems. These connections imply the single-phase or poly-phase inverters which supply the winding. The type of winding influences the performance of the motor. In this paper the performance of the BLDC motor with single-phase connections of the stator coils are studied. So far only three-phase motors were considered and no study for single-phase has been done. The single -phase motor develops the torque with lower ripple that it can be applied for wheelchair. For experimental results, an inner rotor BLDC motor (Laboratory) with rated powers of 1 kW (Fig. 1) have been manufactured and tested by coupled generator (as load).

II. Design of BLDC Motor

Use The BLDC considered for analysis here is a single-phase cylindrical motor with internal rotor as shown in Fig. 2.

Fig. 1 laboratory setup BLDC motor

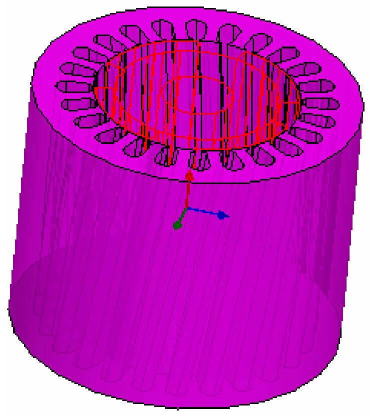

Fig. 2 Inner Rotor Brushless DC motor designed with RMxprt

Structure of stator slots is one of effective parameters on performance of BLDC. For analyzing effects of stator slots structure on motor performance, rotor of BLDC motor (Fig. 3) with RMxprt software is designed.

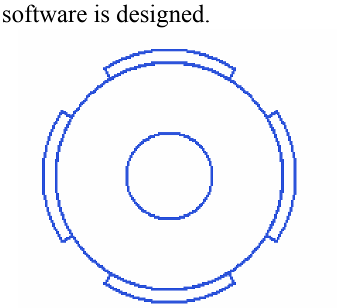

Fig. 3 Rotor of Brushless DC motor

Then stator with three different structures for stator slots is simulated. The efficiency of BLDC is calculated as follows:

$$eff = Pin / Pout \quad (1)$$

$$Pout = Pin - (Pfw - Pcu - Pt - Pfe) \quad (2)$$

III. Finite-Element Analysis of BLDC Motor

The basic physical equations that describe the electromagnetic fields are given by Maxwell's equations [19]:

$$\nabla.B = 0 \tag{3}$$

$$\nabla \times E = -\frac{\partial B}{\partial t} \tag{4}$$

$$\nabla \times H = J \tag{5}$$

Equations, (3)-(5) are presented in terms of the vector field variables E, B and H, but usually these equations are solved using vector potential formulation. The magnetic vector field B can be written in the term of the vector potential as:

$$B = \nabla \times A \tag{6}$$

Also relation between H and B express as fallow:

$$H = r.B \tag{7}$$

Equation of vector potential for magnetic field is obtained by substituting equations (6) and (7) in equation (5):

$$\nabla \times (r.\nabla \times A) = J \tag{8}$$

To solve equations (8) a numerical technique is necessary. Many techniques are available; the most common techniques used are Finite Difference Methods (FDM), Finite Element Methods (FEM), and Boundary Element Methods (BEM). In this paper, the finite element method is chosen. The commercial software selected for this study was Maxwell® 3D, because it is able to solve the coupled electromagnetic and mechanical dynamic equations. This software is also able to solve two and three-dimensional transient electromagnetic problems. In order to solve the model developed in this paper, the three-dimensional version was used. This software required four basic steps to arrive to the problem solution. In the first step the model is drawn and the material and mechanical properties set. Second, the domain is meshed and the boundary conditions are set. Third, the resulting matrix system for the problem is solved and fourth, the post processing analysis is performed. The Maxwell software only uses a triangular element to mesh the domain and linear interpolation functions to approximate the solution.

IV. Simulation and Results

TABLE I
SPECIFICATIONS ADOPTED FOR THE SIMULATED BLDC

NAME	RATING VALUES	UNIT
Rated Power	1	kW
Rated Voltage	220	V
Number of Poles	4	-
Rated Speed	1500	rpm
Number of Stator Slots	24	-
Outer Diameter of Stator	120	mm
Inner Diameter of Stator	75	mm
Minimum Air Gap	0.5	mm
Inner Diameter of rotor	26	mm
Length of Rotor	65	mm
Thickness of Magnet	3.5	mm

Design1: In this case, stator slots are as shown in (Fig.3).In this structure end of slots is arcuate.

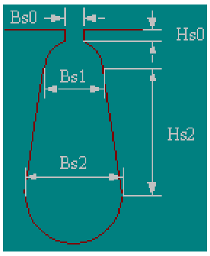

Fig. 4 Slot structure of Brushless DC motor at first state

After designing stator with this type of structure and simulating motor in full-load condition the efficiency is reached to 79.6% that is not suitable for BLDC motor (Fig.5).

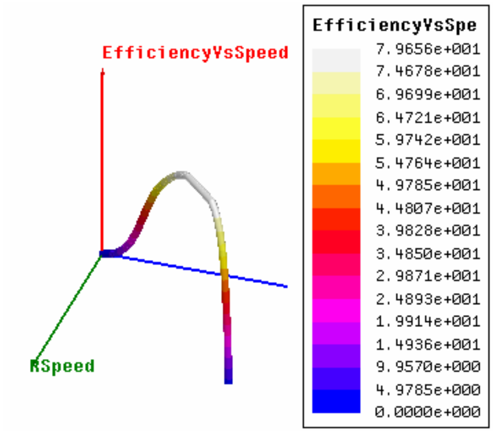

Fig. 5 Efficiency of Brushless DC motor at first state

The BLDC motor is designed and simulated with MAXWELL3D software for analyzing electromagnetically. Fig.6 shows the finite element mesh of the analyzed model.

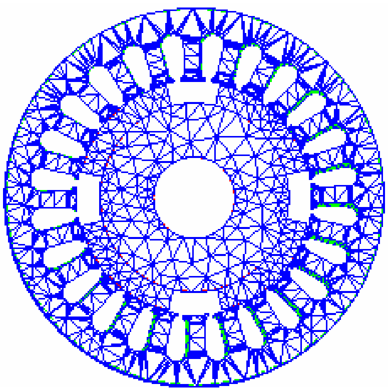

Fig. 6Finite element mesh of BLDC at first state

Fig.6 shows the distributions of the flux density, red stands for the largest flux density and blue is the smallest. Fig.7 shows that the flux density of the inner rotor is apparently larger than that of other areas. Values of flux density in the air gap and inductance leakage are shown in table II.

TABLE II
THE RESULTS OF FINITE ELEMENTE ANALYSIS

NAME	VALUE	UNIT
Air gap flux	0.661	T
Inductance leakage	0.00381	H

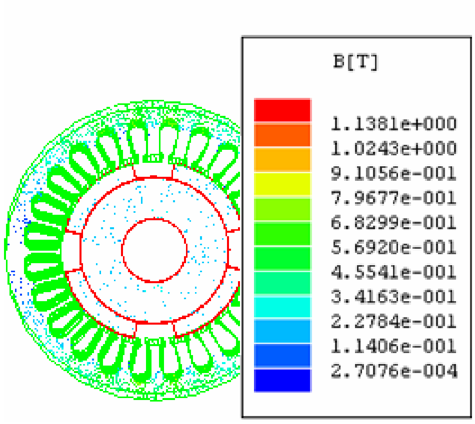

Fig. 7 The flux density of BLDC at first state

Design2: In this state, BLDC motor is designed by changing structure of stator slots according (Fig.8) in this structure length of primary edge is increased. Efficiency of motor is shown in (Fig.9).

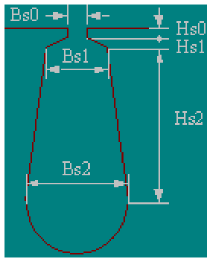

Fig. 8 Slot structure of Brushless DC motor at second state

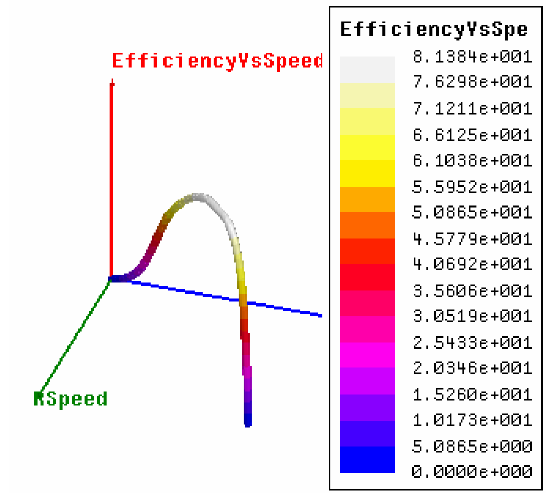

Fig. 9 Efficiency of Brushless DC motor at second state

It is clear from the fig. 9 that by changing stator slots structure efficiency is increased about two percent but still this efficiency is not suitable for BLDC motor. The numerical model is developed with the objective of analyzing the behavior of the BLDC motor electromagnetically. Finite element mesh of the analyzed model and distributions of the flux density are shown in Fig.10 and Fig.11 respectively. It clear from the results of table III that flux density in air gap is increased and inductance leakage in motor is decreased that cause to increasing efficiency.

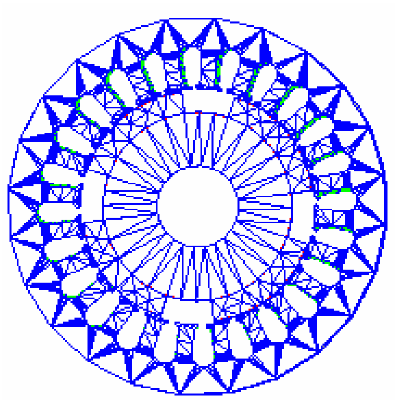

Fig. 10 Finite element mesh of BLDC at second state

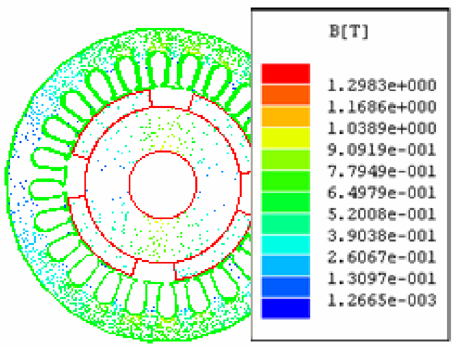

Fig. 11 The flux density of BLDC at second state

TABLEIII
THE RUSULTS OF FINITE ELEMENT ANALYSIS

NAME	VALUE	UNIT
Air gap flux	0.675	T
Inductance leakage	0.00272	H

Design3: In this state against two previous cases depth of slots is increased and also end of stator slots are flatted, stator slots are as shown in (Fig.12).

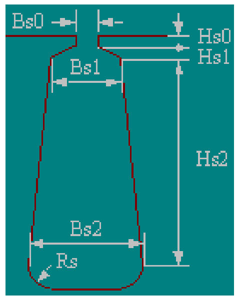

Fig. 12 Slot structure of Brushless DC motor at third state

Fig.13 shows efficiency of simulated motor. The results indicate that the efficiency in compared with two previous states is increased significantly.

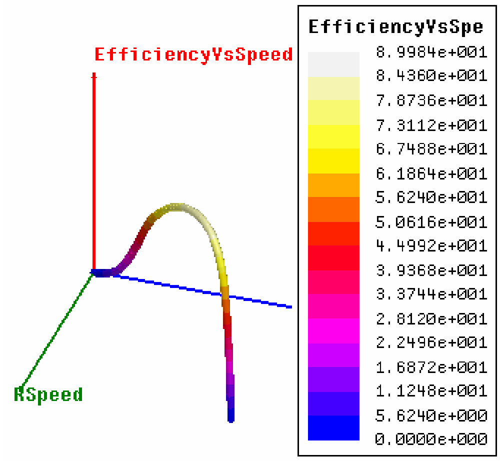

Fig. 13 Efficiency of Brush less DC motor at third state

The numerical model is developed with the objective of examining the behavior of the BLDC. Finite element mesh of the analyzed model and distributions of the flux density are shown in Fig.14 and Fig.15 respectively. It clears from the results of table. IV that flux density in air gap is increased about 0.03 Tesla and inductance leakage in motor is decreased that cause to increasing efficiency.

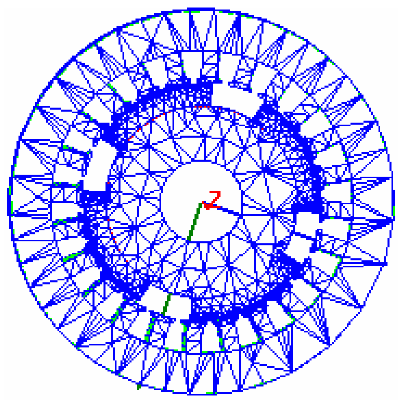

Fig. 14 Finite element mesh of BLDC at third state

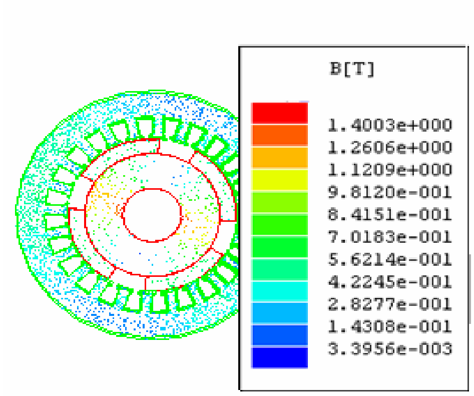

Fig. 15 The flux density of BLDC at third state

TABLE IV
THE RESULTS OF FINITE ELEMENTE ANALYSIS

NAME	VALUE	UNIT
Air gap flux	0.705	T
Inductance leakage	0.00112	H

The results shows that stator slots play an important role in improving efficiency BLDC motor and by changing the structure of stator slots efficiency will be changed. Of course for more improvement of motor performance switching angle of inverter should be analyzed and optimal angle should be determined.

V. Influence of Switching Angle on Motor Performance

Due to the high-speed operation, the winding inductance causes a significant phase delay in the current waveform. The results in the current and the emf waveforms being out of phase, and a negative torque component is generated, with a consequent reduction of the overall torque. In order to get motor better performance Phase commutation advanced is often employed. In DC brush motor the commutation angle is determined by the position of brushes and is kept constant. In BLDC motors the switching angle may vary accordingly to the controller of the inverter that is used. The supply-inverter-motor circuit model is shown in Fig.16.

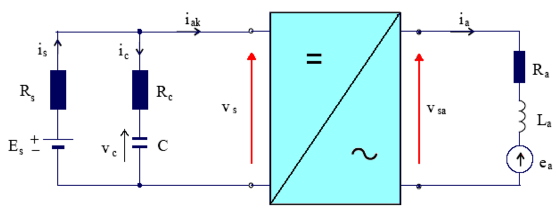

Fig. 16 Circuit diagram of supply-inverter-motor system

The inverter considered for the brushless motor with two-phase winding is shown in (Fig.17). The position sensors are placed between the coils in the intervals of 90 degree .These sensors sense the position of the rotor and they trigger the transistors so that they switch on the respective stator winding.

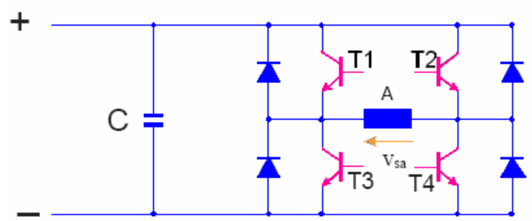

Fig. 17Inverter considered for BLDC with single-Phase Winding

As the switching angle is advanced, the difference between back-emf and the supply voltage increases, and the torque thereby increases. However, there exists an optimal advanced angle, beyond which the drive performance deteriorates. The simulation was done for the following switching angles $\beta = -20^\circ, -30^\circ, -40^\circ, -45^\circ$

The results of simulation were plotted in the form of characteristics of average values of the efficiency, input current and mechanical power output shown in Figs 18, 19 and 20.

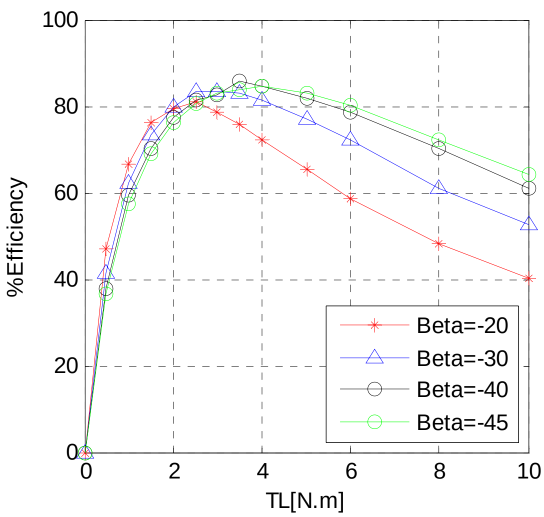

Fig. 18 Efficiency (Eff) vs. load torque (TL)

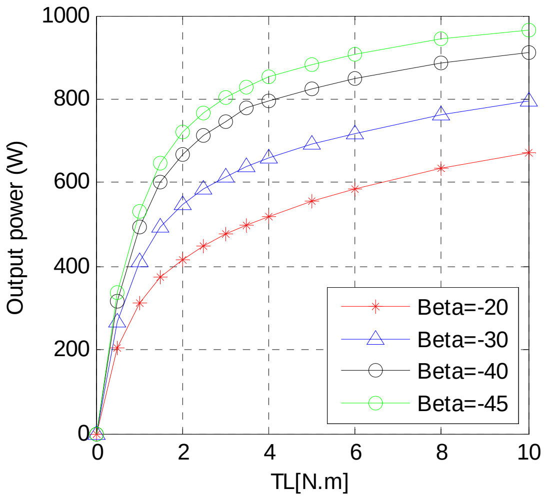

Fig. 19 Mechanical power output (Pem) vs. load torque (TL)

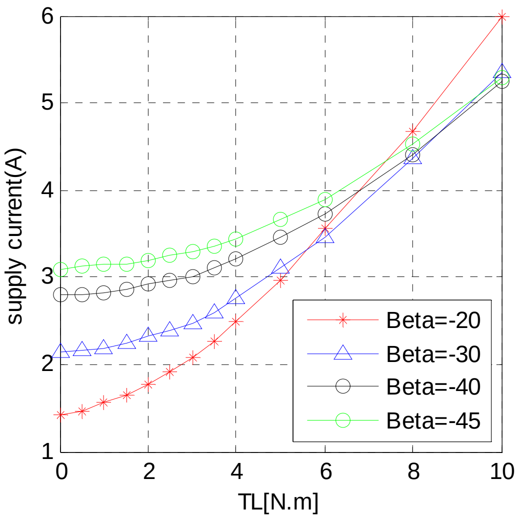

Fig. 20 Input current (Is) vs. load torque (TL)

The characteristics were drawn in the MATLAB from the results obtained in simulation using dynamic model of the motor. The efficiency was calculated as same as section II. The motor efficiency is maximum when the switching angle $\beta = -40^{\circ}$ at load torque 4 Nm, which means transistors are switched much earlier and the motor efficiency is minimum when $\beta = -20^{\circ}$.

VI. Conclusion

The numerical model was developed with the objective of examining the behavior of the BLDC motor. It can be concluded that stator slots play an important role in improving efficiency BLDC motor. By changing the structure of stator slots efficiency is changed. Hence, care should be taken in choosing the best structure for permanent magnets which yields maximum efficiency. It concluded from finite element method that the largest flux density and the smallest inductance leakage is the result of the third case. A study done on the influence of switching angle on motor performance shows that motors operate better when the windings are switched ON earlier with respect to the emfs induced in them. It means the inverters should operate at the advanced switching angle if voltage inverters are applied.

References

[1] G. O. Young, "Synthetic structure of industrial plastics (Book style with Praveen, R.P. Ravichandran, M.H. Sadasivan Achari, V. T. Jagathy Raj, Design and analysis of zero cogging Brushless DC motor for spacecraft applications, *Electrical Engineering/Electronics Computer Conference, Vol. 21, pp. 254- 258, 21-22 May 2010.*

[2] shak, D. Manap, N.A.A. Ahmad, M.S. Arshad, M.R., Electrically actuated thrusters for autonomous underwater vehicle, *Advanced Motion Control, 11th IEEE International Workshop, Vol. 32, pp. 619- 624, 21-24March2010.*

[3] J ong Hyun Choi, Jung Hoon Kim, Dong Ho Kim, Design and Parametric Analysis of Axial Flux PM Motors with Minimized Cogging Torque, IEEE Transactions on *Magnetics, Vol. 45, pp. 2855 - 2858 19 May. 2009.*

[4] Guoping Peng, Research on energy conversion control for small-scaled brushless DC wind power system, *IEEE Transaction Control System, vol. 9 n. 4, July 2004, pp. 629–636.*

[5] Fengge Zhang, Nikolaus Neuberger, Eugen Nolle, Peter Gruenberger, Fengxiang Wang, A New Type of Induction Machine with Inner and Outer Double Rotors, *IEEE International Conference on Power Electronics and Motion Control, Vol. 1, pp. 286-289, Jan. 2004.*

[6] K. T. Chau, Y. B. Li, J. Z. Jiang and S. X. Niu, Design and control of a PM brushless hybrid generator for wind power application, *IEEE Transaction on Magnetics, Vol. 42, n. 10, pp.349−356 ,6-8 September 2006.*

[7] D. Zhang, K.T. Chau, S. Niu and J.Z. Jiang, Design and analysis of a double-stator cup-rotor PM integrated-starter-generator, *IEEE IASAnnual Meeting, pp. 20-26, Feb. 2006.*

[8] Y. Zhang, K. T. Chau, J. Z. Jiang and D. Zhang, A finite element analytical method for electromagnetic field analysis of electric machines with free rotation, *IEEE Transaction on Magnetics, Vol. 42 n. 10, January 2006, pp. 303−309.*

[9] Ghazanfar Shahgholian, Jawad Faiz, Navid Sedri, Pegah Shafaghi, *Mehdi Mahdavian, Design and Experimental Analysis of a High Speed Two-Phase Induction Motor Drive for Weaver Machines Applications*, International Review of Electrical Engineering (IREE), Vol. 5 N. 2, April 2010, pp. 106-112.

[10] Jang, S.-M., H.-W. Cho, and S.-K. Choi," Design and analysis of at high speed brushless DC motor for centrifugal compressor," *IEEE Transactions on Magnetics, Vol. 43, No. 6, 2573-2575, June* 2007.

[11] Rabinovici, R., Magnetic field analysis of permanent magnet motors," *IEEE Transactions on Magnetic, Vol. 32, No. 1, 265-269, January 1996.*

[12] Qiu, Z.-J., J.-D. Xu, G. Wei, and X.-Y. Hou, "An improved time domain finite element-boundary integral scheme forelectromagnetic scattering from 3-D objects," *Progress InElectromagnetics Research, PIER 75, 119-135, 2007.*

[13] C. Depollier,"The three exact components of the magnetic field createdby a radially magnetized tile permanent magnet," *Progress In Electromagnetics Research, PIER 88, 307*-319, 2008.

[14] K. Atallah and D. Howe, "A novel high performance magnetic gear," *IEEE Trans. on Magnetics, Vol. 37, No. 4, pp. 2844−2846, 2001.*

[15] R. Datta and V.T. Ranganathan, "A method of tracking the peak power points for a variable speed wind energy conversion system," *IEEE Trans. on Energy Conversion, Vol. 18, No. 1, pp. 163−168, 2003.*

[16] Z. Q. Zhu and D. Howe," Influence of design parameters on cogging torque in permanent magnet machines, "*IEEE Trans. on Energy Conversion, Vol. 15, No. 4, pp. 407−412, 2000.*

[17] Tae Heoung Kim, Jae-Hak Choi, Kwang Cheol Ko, and Ju Lee,"Finite-Element Analysis of Brushless DC Motor Considering Freewheeling Diodes and DC Link Voltage Ripple, "*IEEE Trans. On Magnetics*, Vol. 39, No. 5, pp.3001−3003, 2003.

[18] Wang Fengxiang; Wang Jiqiang, Kong Zhiguo, Zhang Fengge," Radial and Axial Force Calculation of BLDC Motor with Passive Magnetic Bearing, *Proceedings of ICIEA* 2007 pp.618-621. 23-25 May 2007.
[19] Fengge Zhang, Guangwei Liu, Yongshan Shen, "Characteristic Study on a Novel PMSM with Opposite-rotation Dual Rotors," *Proceeding of International Conference on Electrical Machines and Systems, vol. 50, no. 5, pp. 920–935 8-11 Oct. 2007.*
[20] M. Jafarboland, A. A. Nekoubin, Design and Optimization of a Double-Sided Linear Induction Based on Finite Element Method, International Review of Electrical Engineering (IREE), Vol. 5 n. 3, June 2010, pp. 116-124.