



# Finite Element Analysis of an Exterior Rotor Permanent Magnet Brushless DC Motor for Torque Improvement by a Novel Peak Torque Excitation Technique

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**Abstract** – A novel excitation technique has been proposed for Exterior Rotor Permanent Magnet Brushless Direct Current (ERPMBLDC) motor to improve its torque by Peak Torque Excitation (PTE) technique. Three phase windings of the stator of ERPMBLDC motor are not only excited according to the rotor position but also at phase angles corresponding to peak torque. Phase angles for maximum torque and torque were identified through simulation of ERPMBLDC motor by using Finite Element Method Magnetic 4.2(FEMM4.2) software package. A prototype model was developed which shows good agreement with simulation results.

**Keywords:** Exterior rotor brushless Permanent Magnet DC Motor, Finite Element Method (FEM), Magnetic Vector Potential and torque.

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## 1. Introduction

The impressive improvement in power electronic switching devices, integrated circuits, developments and refinements in permanent-magnetic materials, and manufacturing technology have led to the development of brushless permanent-magnet motors that offer significant improvements in power density, efficiency, and noise reduction. Brushless permanent-magnet motors are especially demanded in clean and explosive environments such as aeronautics, robotics, food and chemical industries, electric vehicles, medical instruments, and computer peripherals [4],[5] and[6]. PM D.C. Brushless Motors use direct feedback of the rotor angular position so that the input armature current can be switched, among the motor phases, in exact synchronism with the rotor motion. This concept is known as self-controlled synchronization, or electronic commutation. The electronic inverter and position sensors are equivalent to the mechanical commutator in D.C. motors [6].

There are several reasons for the overwhelming prevalence of motors having inner rotors [5]. These reasons include the ease of heat removal, because the windings are on the outside, and the containment of the rotating element. In some applications, these attributes are not as important as the benefits gained from having an outer rotor and inner stator. Motors having this construction are sometimes called inside-out motors. Outer rotor motors appear most commonly as spindle motors for hard disk drives and as the drive motor for ventilation fans, such as those used to cool CPUs and computer cases. In these applications, the motor becomes an integrated part of a larger structure. Although individual magnets can be used in outer rotor motors, it is common to use a single bonded magnet ring inside a rotor. Since the stator teeth point outward, this motor is relatively easy to wind. For a given outer radius, an outer rotor motor has a much larger air gap radius than that of an inner rotor motor. As a result, higher torque is achievable, provided the ohmic losses the stator windings can be dissipated [8] and [10].

In the analysis of the electrical machines, the problems are almost always nonlinear due to the presence of ferromagnetic materials. Good designs will typically operate at or near the saturation point. The magnetic permeability or reluctivity is nonhomogenous and will be a function of the local magnetic fields which are unknown at the start of the problem. The most popular method of dealing with nonlinear problems in magnetic is the Newton–Raphson method. Newton–Raphson procedure is applied to linearize the nonlinear system equations[7].The nonlinear magnetic field finite element analysis can provide accurate results .The finite element method is used as it is quicker and easier for the designer. It offers well-known topologies of rotor, stator, winding and methods of analysis.

The finite element method (FEM) has proved to be particularly flexible, reliable and effective in the analysis and synthesis of power-frequency electromagnetic and electromechanical devices .Even in the hands of non specialists, modern FEM packages are user friendly and allow for calculating the electromagnetic field distribution and integral parameters without detailed knowledge of applied mathematics. The FEM can analyze PM circuits of any shape and material. There is no need to calculate reluctances, leakage factors or the operating point on the recoil line. The PM demagnetization curve is input into the finite element program which can calculate the variation of the magnetic flux density throughout the PM system. An important advantage of finite element analysis over the analytical approach to PM motors is the inherent ability to calculate accurately armature reaction effects, inductances and the electromagnetic torque variation with rotor position (cogging torque) [2]-[3], [8] and [13].In electrical machine problems four methods of calculating forces or torques are used: the Maxwell stress tensor, the co-

energy method, the Lorentz force equation, and the rate of change of field energy method. The most appropriate method is usually problem- dependent, although the most frequently used is the Maxwell stress tensor method [12].

FEMM package is an open source, simple, accurate, and low computational cost freeware product, popular in science and engineering. Several applications in areas such as Electromagnetic, Materials Science, Industry, Medicine, Experimental and Particle Physics, Robotics, Astronomy, and Space Engineering can be found. The software is reasonably fast and accurate, user friendly, and freely distributed. The last seems to be its main advantage concerning its educational value. Its capability to meet as a complementary tool the needs of teaching electromagnetic in higher education will be explored and evaluated [1].

In the proposed model FEMM4.2 software package has been used to investigate the excitation currents to the different phases of stator windings and corresponding torque developed to enhance the torque produced by ERPMBLDC Motors.

## 2. Modeling and Simulation of ERPMBLDC Motor

ERPMBLDC motor has been modeled by using FEMM4.2 software. It involves preprocessing, present processing and post processing to simulate the designed motor model. The following algorithm has been used to simulate the excitation of the stator windings of the motor at phase angles corresponding to peak torque i.e. peak torque excitation (PTE) technique.

### 2.1 Algorithm

Simulation of the ERPMBLDC motor with PTE technique is simulated by the following algorithm

1. Stator is given with a three phase supply.
2. Rotor is rotated from 0 to 87.5 degree with 2.5 degree as periodic interval.
3. At every interval,

- I. Phase angle  $\theta$  is computed using the formula
 
$$\theta = (K * 5 * (3.14)) / 180 \quad (1)$$

Where K varies from 0 to 72 linearly

- II. The torque value against each phase angle is noted and the phase angle which yields maximum torque is identified.
- III. Prototype trigger points are calculated from the torque value and the phase angle.
- IV. Current, voltage, speed and torque values are computed.
- V. The torque values are found to be high when compared to the conventional method.

## 3. Simulation of ERPMBLDC Motor

The objective of anticipated methodology is to compute the flux pattern, magnetic flux density and torque in eight pole, ERPMBLDC Motor. FEMM4.2 is a software suite for solving low frequency two dimensional electromagnetic problems. Motor Model is shown in Figure 1 in axisymmetry domain.

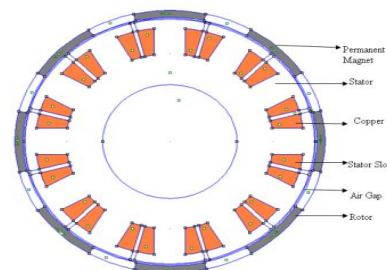


Figure 1 Motor Model

The procedure for implementing the numerical computation of magnetic field problems using the finite element method involves three main steps. They are pre-processing, present-processing and post-processing.

### 3.1. Pre-Processing

This pre-processing is used for drawing the problems in geometry, defining materials and defining boundary conditions. The derivation of the finite element model of ERPMBLDC motor under consideration involves defining conduction materials, electromagnetic materials and their properties and boundary conditions and eventually results in mesh generation.

Thus entire ERPMBLDC Motor solution region defined by materials, circuit properties and boundary conditions is broken down into 11419 triangular elements and 5894 nodes before mathematical computation is carried out to obtain magnetic field distribution with the cross section of the motor.

### 3.2. Present- Processing

Solving the problem by the Maxwell's equations for magneto static problems in which fields are time-invariant, the field intensity H and flux Density B must obey:

$$\nabla \times H = J \quad (2)$$

$$\nabla \cdot B = 0 \quad (3)$$

The field intensity and flux density of a material may be related as:

$$B = \mu H \quad (4)$$

Where H= magnetic field intensity A/m, J= current density A/m<sup>2</sup>, E = electric field V/m, B= flux density W/m<sup>2</sup>(or) tesla,  $\mu$  = permeability of the material H/m and A= magnetic vector potential Web/m.

FEMM4.2 finds a field that satisfies the above equations (2), (3) and (4) via a magnetic vector potential approach. The flux density may be written in terms of the vector potential, A as:

$$B = \nabla \times A \quad (5)$$

This definition of B always satisfies equation (2) can be rewritten as:

$$H = \frac{B}{\mu} \quad (6)$$

$$H = (\nu \nabla \times A) \quad (7)$$

$$\nabla \times (\nu \nabla \times A) = J \quad (8)$$

Where A is the axial component of the magnetic vector potential is the current density, and  $\nu$  is the reluctivity of the material. In the area of the stator conductor, the magnetic field equation can be represented as

$$\nabla \times (\nu \nabla \times A) - J = 0 \quad (9)$$

The Finite Element Method Magnetics retains the form of equation (9) so that magneto static problems with a nonlinear B-H relationship can be solved. The advantage of using vector potential formulation is that all the conditions to be satisfied have been combined into a single equation. If A is found, B and H can then be deduced by differentiating A. Obtaining the field distribution in the analyzed domain of the geometry for the ERPMBLDC Motor at arbitrarily chosen excitations and loading conditions is designed to get the flux.

### 3.3. Post- Processing

This is the process for calculating and presenting ERPMBLDC motor flux pattern and deducing required results as well as parameters from the analyzed model.

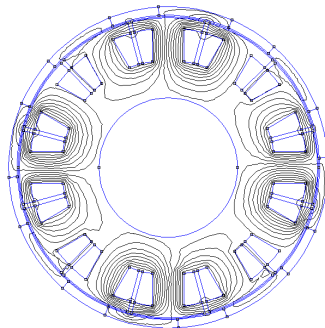


Figure 2 Flux plot

The finite element analysis allows for fast parameterization to scrutinize the magnetic flux density distribution. Figure 2 shows flux plot obtained from the computations, Flux lines are flowing from stator coil to the air gap and concentrate at pole centers of alternate poles.

## 4. Simulation Results

The three phase stator windings are excited by varying phase currents A, B and C at the phase angles from  $0^{\circ}$ - $360^{\circ}$  with interval of  $5^{\circ}$  i.e. totally 73 iterations for each rotor position. The corresponding torque values are investigated. This procedure is repeated for rotor angles from  $0^{\circ}$ -  $90^{\circ}$  with an increment of  $2.5^{\circ}$ , but for simplicity torque for various phase angles from  $0^{\circ}$ - $360^{\circ}$ . For each rotor position peak torque value is determined and in total 36 rotor positions are studied for one quadrant. As the motor model is being axisymmetry investigations are carried out for one quadrant. Peak torques and the corresponding phase angles are identified and the motor is simulated and average torque is obtained.

## 5. Hardware Implementation of ERPMBLDC Motor

Proposed concept has been implemented in a prototype model in order to validate the simulation results. In hardware implementation a three phase MOSFET based inverter has been used to excite the stator winding of ERPMBLDC motor. Six MOSFETS (Model STP55NF06) have been driven by MOSFET driver TLP250. Here switching sequence of the MOSFETS has been programmed by using ATMEGA16 microcontroller which generates six driver signals to excite the stator windings at phase angle corresponding to peak torque.

In this proposed circuit at any moment in three phases of ERPMBLDC motor two phase windings are to be in conducting state and one phase winding is to be in non conducting state. Each phase winding conducts for  $120^{\circ}$  and non conduct for  $60^{\circ}$  both in positive and negative directions whereas the phase shift between adjacent phases is  $60^{\circ}$ . Floating phase is used to carry back EMF which gives information about rotor position. The back EMF signals are conditioned and given to the microcontroller ATMEGA16. Based on the received back EMF signals the microcontroller generates six driver signals to drivers. Figure3 Shows Circuit Diagram of developed hardware circuit for PWM controlled MOSFET based inverter driven ERPMBLDC motor.

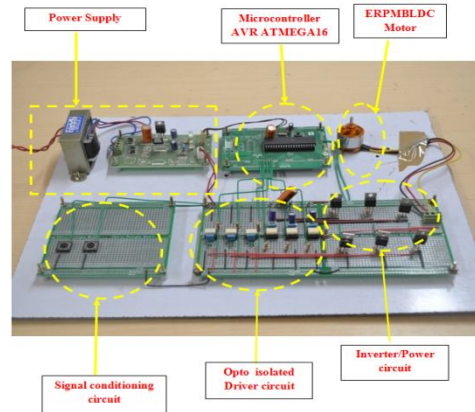


Figure 3 Photograph of ERPMBLDC Motor driver circuit

Figure 4 shows the phase to phase voltages waveform of proposed peak torque method. Torque developed by the proposed technique has been calculated by using the following equations.

$$\text{Peak torque} = (I \times K_t) \text{ in N-M} \quad (10)$$

Where,

$$\text{Torque constant } K_t = K_b \times 1.345 \quad (11)$$

$$\text{Voltage constant } K_b = \frac{\text{Voltage}}{\text{Speed}} \quad (12)$$

In this model at any time two conducting phases are used for exciting the stator winding to run the rotor in forward direction at possible peak torque by sensor less control. Here the non conducting phases are used for obtaining back EMF signal to identify rotor position. It is possible to determine when to commutate the motor drive voltages by sensing the back EMF voltage on an undriven motor terminal. The obvious cost advantage of sensor less control is the elimination of the Hall position sensors.

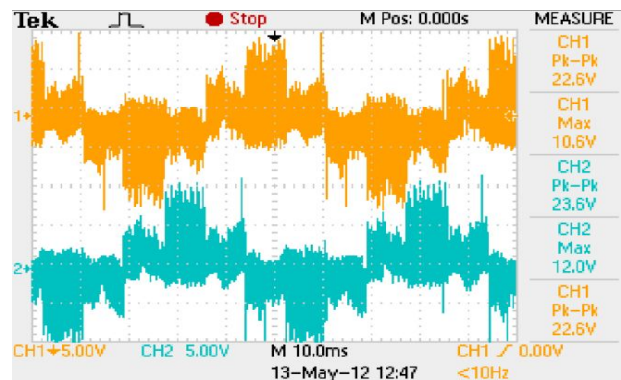


Figure 4 Peak torque method

A few other schemes for sensorless BLDC motor control were also reported in the literature. The back EMF integration approach has the advantage of reduced switching noise sensitivity and automatic adjustment of the inverter switching instants to changes in the rotor speed [14]. The back EMF integration still has accuracy problems at low speeds. The rotor position can be determined based on the stator third harmonic voltage component [15]. The main disadvantage is the relatively low value of the third harmonic voltage at low speed. In [16], the rotor position information is determined based on the conducting state of free-wheeling diodes in the unexcited phase. The sensing circuit is relatively complicated and low speed operation is still a problem.

## 6. Results and Discussion

The magnetic parameters like magnetic flux pattern, distribution of the magnetic flux and at each rotor position phase angle corresponding to peak torque were determined. Peak torques and its corresponding phase angles for various rotor positions by simulation were tabulated. Torque developed prototype for various rotor angles were also tabulated in Table 1. It shows Comparison between the torque developed by Peak torque method by hardware and Peak torque method by simulation.



Table 1

Comparison between the torque developed Peak torque method by hardware and Peak torque method by simulation

Rotor angle	Peak torque method by hard ware	Peak torque method by simulation
	Torque (N-M)	Torque (N-M)
5 <sup>0</sup>	0.0385	0.0376
32.5 <sup>0</sup>	0.0776	0.0786
47.5 <sup>0</sup>	0.0807	0.0791
62.5 <sup>0</sup>	0.0775	0.0786

## 7. Conclusion

Computational procedure for the finite element modeling of ERPMBLDC Motor has been presented. A two dimensional magnetic field model of ERPMBLDC Motor has been developed. FEMM4.2 is an excellent tool for electromagnetic field mapping, by which one could obtain electrical machine variables easily. The proposed novel PTE technique has been simulated by using FEMM4.2. It yields the maximum average torque for any rotor position. These results are verified by experimental results which hold good agreement.

## References

- [1] J Konstantinos B. Baltzis, Springer Science + Business Media, Educ Inf Technol 2010 15:19–36, "The finite element method magnetics (FEMM) freeware package: May it serve as an educational tool in teaching electromagnetics?"
- [2] E.N.C. Okafor, P.E. Okon and I.C.C. Okoro, *Journal of Applied Sciences Research*, 5(11): 1889-1898, 2009, INSInet Publication, "Magnetic Field Mapping of a Direct Current Electrical Machine Using Finite Element Method".
- [3] K. B. Baltzis\*, Thessaloniki, April 2008, "The FEMM Package: A Simple, Fast, and Accurate Open Source Electromagnetic Tool in Science and Engineering"
- [4] Alexandre Pages, Guillaume Lacombe, Fabrice Marion, Xavier Brunotte, Ronan Le Letty (1) Cedrat Groupe - 15, chemin de Malacher - Inovallée - 38246 MEYLAN Cedex – France, ACTUATOR 2008, *11th International Conference on New Actuators, Bremen, Germany*, 9 – 11 June 2008, "Upgrade of Miniature Outrunner Brushless DC Motors".
- [5] Łukasz Knypiński, Poznan University of Technology, X International PhD Workshop OWD'2008, 18–21 October 2008, "The steady-state and transient FEM analysis of the outer rotor permanent magnet brushless DC motor".
- [6] Satish rajagopalan, member, wiehan leroux, Thomas G. Habetler, and Ronald G. Harley, IEEE Transactions on power electronics, VOL. 22, NO. 5, September 2007, "Dynamic Eccentricity And Demagnetized Rotor Magnet Detection In Trapezoidal Flux (Brushless Dc) Motors Operating Under Different Load Conditions".
- [7] M. A. Jabbar, Hla Nu Phyu, Zhejie Liu, and Chao Bi, IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS, VOL. 40, NO. 3, MAY/JUNE 2004, "Modeling and Numerical Simulation of a Brushless Permanent-Magnet DC Motor in Dynamic Conditions by Time-Stepping Technique".
- [8] Dr. Duane Hanselman, Electrical and Computer Engineering' University of Maine' Orono, ME 04469, USA, Magna Physics Publishing-2006, "Brushless Permanent Magnet Motor Design" Second Edition.
- [9] T. J. E. Miller, Mircea Popescu, Calum Cossar, and Malcolm McGilp, IEEE Transactions on Magnetics, VOL. 42, NO. 7, JULY 2006, "Performance Estimation of Interior Permanent-Magnet Brushless Motors Using the Voltage-Driven Flux-MMF Diagram".
- [10] Udaya K. Madawala, and John T. Boys, IEEE TRANSACTIONS ON MAGNETICS, VOL. 41, NO. 8, August 2005, "Magnetic Field Analysis of an Ironless Brushless DC Machine".
- [11] Jacek F. Gieras United Kingdom, 2002, "Permanent Magnet Motor Technology" Design and Applications Second Edition, Revised and Expanded.
- [12] A. Kostaridis, C. Soras, V. Makios, 2001 John Wiley & Sons, Inc. "Magnetostatic Analysis of a Brushless DC Motor Using a Two-Dimensional Partial Differential Equation Solver".
- [13] M.V.K. Chari, S.J. Salan, Rensselaer polytechnic institute troy, new york-2000, "Numerical Methods In Electromagnetism".
- [14] K. Uzuka, H. Uzuhashi, "Microcomputer Control for Sensorless Brushless Motor," IEEE Trans. Industry Application, vol. IA-21, May-June, 1985.
- [15] R. Becerra, T. Jahns, and M. Ehsani, "Four Quadrant Sensorless Brushless ECM Drive," IEEE Applied Power Electronics Conference and Exposition 1991, pp.202-209.
- [16] J. Moreira, "Indirect Sensing for Rotor Flux Position of Permanent Magnet AC Motors Operating in a Wide Speed Range," IEEE Industry Application Society Annual Meeting 1994, pp.401-407.