

Minimization of Cogging Torque and Current Control in Brushless DC Machine by Co-simulation Process

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Abstract - This paper deals with a comprehensive study on reducing cogging torque generated in Brushless DC motor drives (BLDC). In such drives, cogging torque suppression techniques that are practically effective in low speed as well as high speed regions are scarcely found in literature. A well-known skewing technique is adapted in the stator slots to reduce the cogging torque using CAD package Magnet 6.1.1. This paper addresses also the problem of phase current control using 3-phase bridge inverter. By the co-simulation interfacing of the PSIM 6.1 and Magnet software, the designed machine is controlled. This is based on a strategy that the current slopes of the incoming and outgoing phases during the commutation interval can be equalized by a proper duty-ratio control scheme. The proposed control method accomplishes suppression of spikes and dips super imposed on the current and torque responses during the commutation intervals of the inverter. The effectiveness of proposed control method is verified through simulation methods.

Keywords: -BLDC motor, skewing, cogging torque.

I. INTRODUCTION

Brushless dc motors with trapezoidal back-EMF have been widely used due to their high power density and easy control method. Moreover, basic trapezoidal brushless dc motors make it possible to use a single dc current sensor to regulate the phase current flowing through two motor phases. The commutation torque ripples usually occur due to the loss of exact phase current control during the phase commutation intervals. It shows the commutation torque ripple in trapezoidal brushless dc motors, including torque spikes in the low speed range and torque dips in the high speed range. A theoretical analysis related to these commutation torque ripples in literature [2]-[3]. As for brushless dc motor drives with three phase current sensors, many researches regarding commutation torque ripple have been carried out [4]-[5].

Methods for reducing the commutation torque ripple in brushless dc motors with a single current sensor have been reported in the literature. A phase voltage control adjusts duty ratio applied during commutation intervals to reduce the torque ripple [4]-[5]. An overlap switching method by which the turn-off timing instant of the outgoing switch delayed is presented [1]-[8]. A current control with a chopping action activated only during

commutation intervals reduces the peak current appeared in the un-commutated phase [5].

The paper presents a commutation ripple suppression method in dc drive with only a single current sensor. A dead-beat current controller is employed to enhance the current control performance. The proposed control scheme makes the commutation current slopes of the incoming and outgoing phases balanced during the commutation interval of the phase currents. This new torque ripple suppression technique provides attractive performance over the entire speed range.

Torque ripple improvements in brushless dc miniature motors are devised [1]-[8]. The wavelet decomposition approach is discussed and applied to compare the problem. The paper [6] studies the recent trend of the analysis the torque ripple due to phase commutation in brushless dc machine. The problem analyzed and reviewed. [7]-[9] analyze the current control algorithm to reduce the torque ripple in brushless dc motor. [4]-[5] discussed the current control strategy is trapezoidal in EMF actuators to minimize the torque ripple due to phase commutation. [2]-[3] review the pulsating torque minimization techniques for permanent magnet ac motor drives. [10]-[11] presented the theoretical foundation underlining the construction of machine. This revised the identification and compensation of torque ripple in precision permanent magnet motor drives. Torque ripple reduction can be done in high speed and low speed regions.

II. COGGING TORQUE

Cogging torque is a no-current torque produced due to the interaction between the permanent magnets and the stator teeth. The torque present is a ripple in the output torque. It is an undesired effect that contributes to the output ripple, vibration, and noise in the machine. This torque prevents the smooth rotation of motor. Cogging torque must be reduced.

It is possible to reduce the cogging torque by having a suitable geometric configuration. One of the methods to reduce the cogging torque is by skewing the stator slots. Skew is the arrangement of laminations on a rotor or armature to provide a slight diagonal pattern of their slots with respect to shaft axis. The pattern helps to eliminate cogging effects.

In this paper, FEA based CAD package Magnet 6.1.1 has been used to analyze the cogging profile of an unskewed model and model with skewed stator slots. The unskewed model has been solved in 2D while the skewed model has been solved in 3D and the cogging torque profiles have been compared.

III. FEA BASED SIMULATION USING MAGNET

3.1 Steps in Modeling the Machine:

Modeling the permanent magnet brushless DC motor is a part of preprocessing modeling, the motor in magnet involves 3 steps:

Geometric Modeling:

This step requires knowledge of the exact geometric dimensions of the PMBLDC motor. This is necessary to create the accurate model of the machine.

Material Assigning:

This step requires a clear understanding of the electrical and magnetic properties of various materials so that suitable materials can be chosen for various parts of the motor.

Parameterization:

This step involves changing the various parameters of the model and viewing the effects these changes have on the performance of the motor.

3.2 Machine Specifications

The geometrical dimensions of the machine are designed using MagNet software. The specification of the PMBLDC motor modeled for this project, are given below in Table 1.

The proposed BLDC model designed as per the steps involving in the modeling is shown in Fig 1. The motor has 120-degree symmetry it can be seen from the specifications. So, initially, only a 120-degree section of the un-skewed motor is modeled and the full motor is obtained later by rotating this section.

Table 1 Specification of the Motor

Shaft radius	10mm
Stator radius	42mm
Poles	6
Air gap	1mm
Slot depth	12mm
No of slots	60
No of teeth	60
Length	50mm
Tooth thickness	12mm

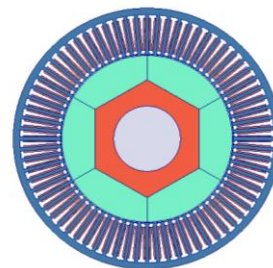


Fig 1 Proposed BLDC Model

IV. SKEWING TECHNIQUE

Since this project deals with the reduction of cogging torque by skewing the stator slots, the second part of modeling involves the skewing of stator slots. The skewed stator slots have been shown in Fig.2.

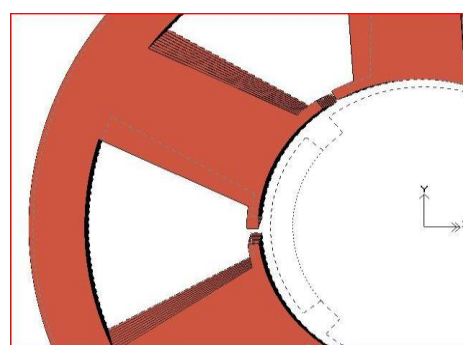


Fig 2 Skewed stator slots

Procedure to Skew

1. The stator slots are selected and its properties window is opened.
2. In the multi sweep option, the set sweep segment tab is chosen and the skew angle is entered.

Once this is done, the skewed model is obtained.

In this project, 2skewed model with

1. Skew angle=5 degree
2. Skew angle=10 degree

Have been designed.(diagram of skewed start slots)

Similarly, any component can be skewed. For e.g. the permanent magnets may be skewed.

The construction of the skewed model completes the modeling stage and now, the unskewed model must be solved in 2D and the skewed model in 3D as shown in Fig.2 is used to obtain the results.

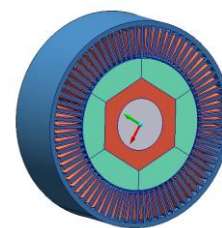


Fig 2 3D view of Skewed model

V. SIMULATION OF MOTOR DRIVES USING PSIM

The motor drives are controlled by 3-phase bridge inverter by using power simulation and the phase voltage and phase current can be controlled by the circuit. The motor drive can be controlled by IGBT using PWM technique. Instead of the motor a general DLL block (dynamic link library) is created to interface the skewed model of BLDC machine.

5.1 Interfacing PSIM AND MagNet

After creating the DLL block providing the input and output ports. The MagNet plug-in for PSIM enables co-simulation between PSIM and MagNet. The voltage and current signals of PSIM are transferred to MagNet during the co-simulation process. This constant data exchange links the two models and produce interdependent multi-domain results. Co-simulations of both the control circuit and the electric machine take into account:

- Eddy currents and material non-linearity
- Mechanical movement
- Complex drive and control circuits

The Interfacing of PSIM and Magnet (Co-simulation process) is shown in Fig.3.

VI. ANALYSIS OF RESULTS

This section explains various FEA techniques used for simulation in Magnet and the method to solve the model in Magnet. It is observed that the torque peak value of un-skewed model is 1.4 Nm and the curve is not smooth. For 5 degree skew angle, the peak value is reduced to 1.2 Nm and the curve is comparatively smoother. The skew angle is further increased to 10 degree and the corresponding peak value of the cogging torque has reduced to 0.74 Nm and the curve is visibly smoother.

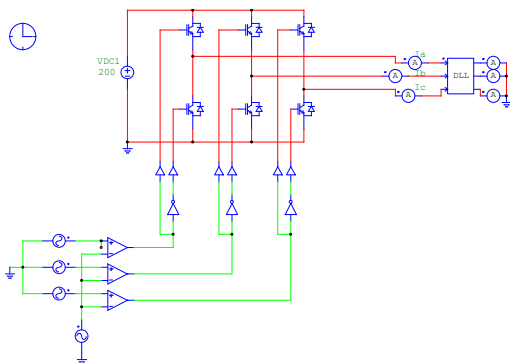


Fig 3. Interfacing of MagNet and PSIM

The cogging torque value at various rotor position for the un-skewed model and two skewed models are shown in the following Figs. 4, 5 and 6.

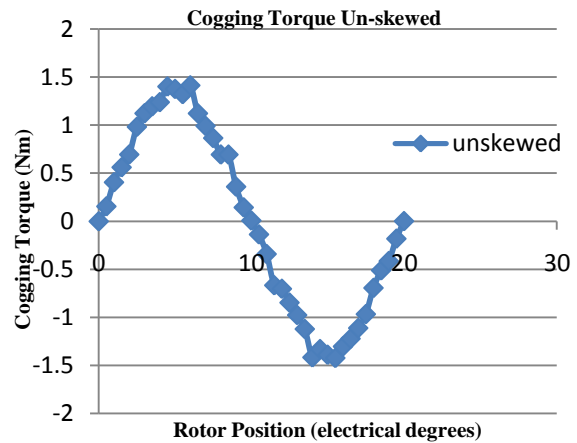


Fig 4 Cogging Torque Profile for the Un-skewed Model

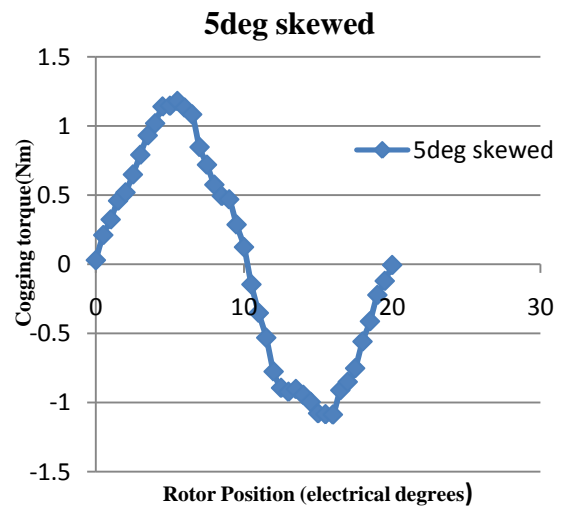


Fig 5 Cogging Torque Profile for 5deg Skewed Model

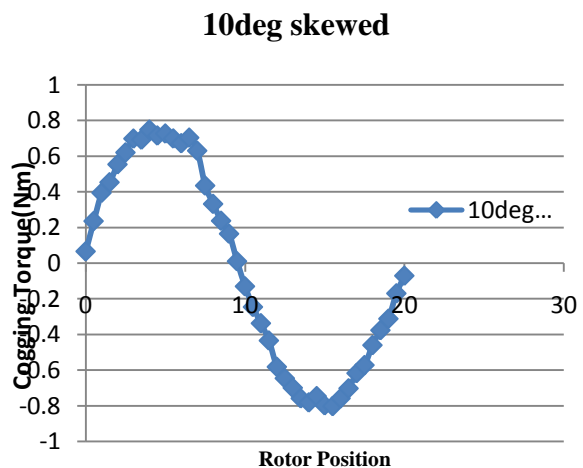
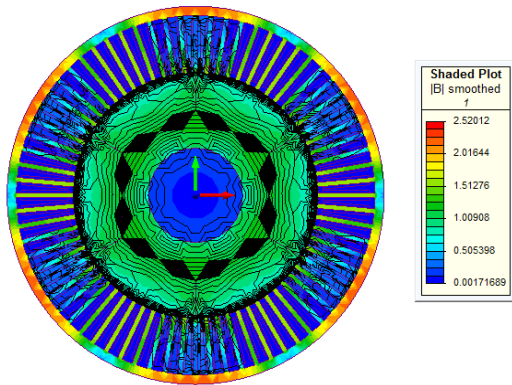


Fig 6 Cogging Torque Profile for 10 deg Skewed Model

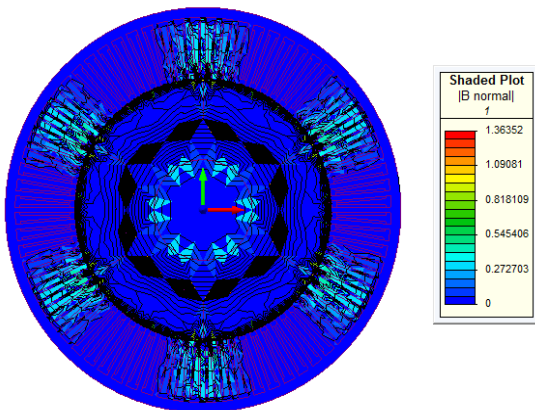
6.1 FLUX PLOTS

As can be seen from the flux plots, in the un-skewed model the flux density is mostly about 1.06 Weber/meter². Fig.7 represents the flux density function of Un-skewed and skewed model of BLDC motor.

1. Magnets and this too is not the maximum flux density attained in the permanent dangerously high.
2. Here the blue region indicates maximum flux density and occurs due to the high reluctance of the region filled with air.
3. But as the skew angle is increased to 10 degrees, there is a change in the flux density distribution. Though the flux density remains the same in many regions, maximum flux density (about 1.4 Weber/meter², indicated by yellow color) is attained in some parts of the stator (in addition to the permanent magnets).
4. Red areas indicate undesirably high flux density and may result in hot spots that may damage the motor. So, as skew angle is increased, the probability of development of hot spots increases.
5. Hence, the change in flux density and development of hot spots must also be considered while skewing the motor to reduce the cogging torque.



(a)



(b)

Fig 7 Flux density of (a) Un-skewed and (b) Skewed Model

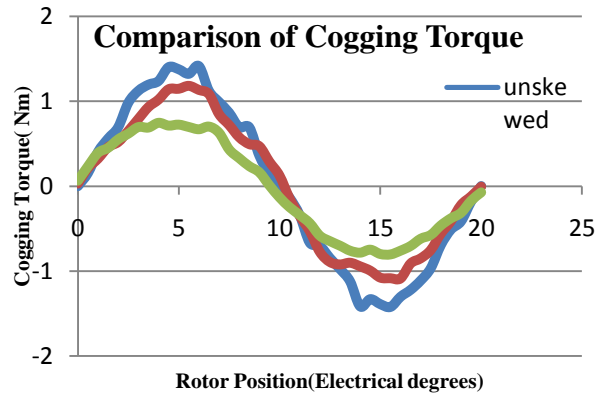


Fig 8 Comparison of Cogging Torque

Table 2 Comparison of Results

Model	Range (Nm)	Positive Peak (Nm)	%Reduction In Range Over The Unskewed Model	%Reduction In Peak Over The Unskewed Model
Unskewed	2.8386306 51	1.4151337 02	-	-
Skewed (5 Deg)	2.2682281 58	1.8117906 8	20.0943	16.533
Skewed (10 Deg)	1.5502958 32	0.7478815 98	45.3858	47.1512

When compared with an un-skewed model, the peak value of cogging torque has reduced by 16.533% for a skew angle of 5 degrees. The peak value is further reduced when the skew angle has increased to 10 degrees. There is a reduction of 47.15% for a skew angle of 10 degrees compared to an un-skewed model. A similar reduction has been observed in the range too. For a skew angle of 5 degrees there is 20.09% reduction compared to an un-skewed model while for a 10 degree skew, there is a 45.39% skew compared to the un-skewed model.

It has also been observed that the smoothness of the curve improves with skewing. Thus, there has been an observed reduction in cogging torque by skewing the stator slots. The comparison of cogging torque waveform and comparison of results has been shown in the Fig 8 and Table 2.

6.2 Simulation for Phase Current

The motor was controlled by the 3-phase bridge circuit using IGBT controlled by PWM technique. This PWM has logical sequence with NOT gate gives the time sequence for ON-OFF switch controller, the unit is controlled by the comparator and sinusoidal voltage source and the phase current and phase voltage was controlled.

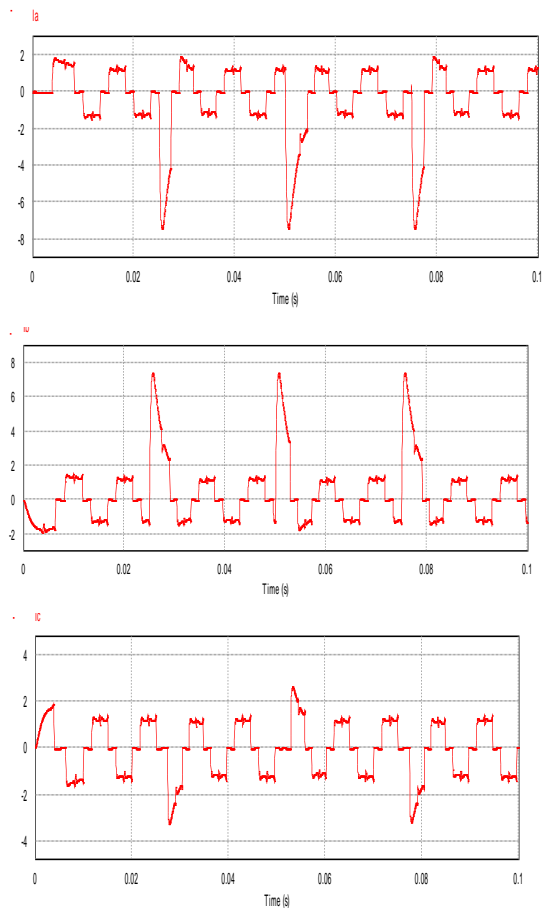


Fig.9 Three Phase Current for BLDC motor

The Three Phase current waveform for the simulation is shown in Fig.9.

VII. CONCLUSION

Brushless motor are inherently more efficient than an ac induction motor because their rotors contain permanent magnets, no electromagnets. Also, variable speed operation, with reduced cogging torque results in system efficiency improvements. In this paper, a reduction in cogging torque will improve the performance of the machine. A marked reduction in cogging torque has been observed. On skewing the stator slots by 10 degrees, the peak value of cogging torque reduces by almost 47%. Cogging torque is compared to different skew angle for enhance the performance of machine. The phase currents are controlled by three phase bridge circuit by using co-simulation process.

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