Influence of a Thin Copper Shield on a BLDC Motor Parameters

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***Abstract*—A simplified model of a brushless DC motor segment is studied in this work. Shielding of the ferromagnetic structure with a high conductivity layer is explored. The shield is supposed to reduce the ohmic losses of the magnets and of the entire structure, particularly at the higher frequencies. In order to verify that, both calculations and measurements of the power loss are accomplished for the model first. In conclusion, locked rotor measurements are performed on a real BLDC motor in order to validate the results.**

***Index Terms*—Eddy current loss, BLDC rotor shielding.**

I. Introduction

MAGNETIC field in a brushless DC (BLDC) motor plays the most important role not only in the torque formation, but also in the loss generation. Besides the fundamental components of the magnetic flux generated by the stator currents, there are high frequency components too, due to both the space harmonics and the time harmonics generated by chopping activity in a modern motor supply. High speed rotor losses due to the space harmonics are well documented in the literature [1-6]. The losses are mostly controlled by lamination and magnet segmentation [7]. High conductivity rotor shield is an option for the loss reduction in the case of a machine with a solid-rotor [6]. Using conductive shield is expected to reduce both losses caused by the time and space harmonics. The ohmic losses, caused by the PWM voltage supplying the stator, are not fully explained in the literature and need more attention. In this paper we study both fundamental frequency and the higher frequencies BLDC motor losses, due to the chopping nature of the supply voltage. The available motor is presented in Fig. 1. The goal of the work is first to evaluate the loss on a simple model and next to extrapolate the conclusions to the real BLDC motor. In the end, some of the results for the model are verified by measurements on the available motor.

Fig. 1. The explored 300W outer rotor BLDC motor.

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II. Materials and Methods

A. The model

A simplified BLDC motor segment model from Fig. 2 is supposed to recreate the magnetic field similar to the one inside the motor. This flat model is studied both by numerical modeling and measurements on a physical model. Commercially available software is used for the calculations. The 2D FEM analysis results for the inductance, resistance and power loss were not satisfactory. Consequently the 3D analysis is employed. Magnetic forces in the segment model are calculated using magnetostatic analysis. In order to explore the copper layer influence, winding impedance and the ohmic losses are calculated using time harmonic analysis. The 3D model for the motor segment from Fig. 2 is explored. The copper layer thickness varies from 0.1 mm to 0.5 mm. For

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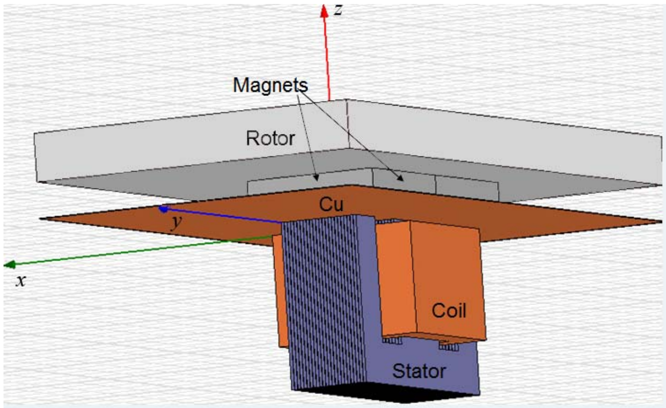

Fig. 2. Simplified model of the BLDC motor segment.

the calculations, the coil is taken to be supplied by the time harmonic current of NI=240 A-turns.

The model from Fig. 2 consists of the parts resembling the stator and rotor of the motor. Influence of the different copper layer thicknesses is studied on the model. The part equivalent to the "Rotor" in Fig. 2 is built from a 7 mm thick solid iron. Neodymium magnets, 5 mm thick, are combined into a flat layer and protected by a 0.1 mm thick plastic sheet. The examined layer is 0.1 mm, 0.35 mm or 0.5 mm thick copper, or alternatively plastic, covered by a 0.1 mm thick plastic protection. The "Stator" to "Rotor" separation was kept constant, but filled with appropriate varying thickness copper or plastic foil. The part representing "Stator" in Fig. 2 is built out of 24 (36x24 mm) E shaped, isolated silicon steel sheets. The individual sheets are 0.5 mm thick including the protective coating. Bulk iron conductivity assumed $\sigma=10.3\cdot10^{6}$ *S/m*. Copper coil is formed by twisting together seven individually insulated conductors of 0.45 mm diameter, in order to reduce skin effect. The number of turns in the coil is 24. The winding is placed around the central leg of the E core, having the cross section in the form of a 12 mm x 12 mm square. Plastic coil former around the wire package is 1 mm thick. The winding area is 16 mmx4 mm. Linearity of iron is assumed, with $\mu_r = 550$.

The stator to rotor gap has immense influence on the magnetic field distribution inside the motor. In the segment considered, the corresponding separation was kept constant and filled with copper foils of different thicknesses, which was not possible for the real motor. For this reason, the calculations are verified by measurements on the physical model of the segment.

B. *The motor*

The available 300 W motor from Fig. 1 is an outer rotor BLDC motor. The spacing between the stator and the rotor of the motor from Fig. 1 is measured to be about 0.4 mm. Consequently, only a very thin copper foil, 0.1 mm thick, together with two insulation layers of 0.1 mm, can be inserted. At the PWM frequency of f=22 kHz, the copper thickness of 0.1 mm represents less than 25% of the skin depth, d=0.44 mm, at the observed frequency.

III. Calculation Results

Numerical solution to the problem is based on the magnetic vector potential, A. The current of the stator coil from Fig. 2 is circumferential. Thus, magnetic vector potential has only horizontal ("x" and "y") components. Numerical results are obtained for the quasi-static case with "x" and "y" oriented induced currents. For the problem of interest, the governing equation for the magnetic vector potential is

$$j\omega\sigma\vec{A}+\nabla\times\left(\frac{1}{\mu_0\mu_r}\nabla\times\vec{A}\right)=\vec{J}\ . \tag{1}$$

Magnetic flux density is calculated first for the different frequencies. Fig. 3 represents the flux density distribution at 50 Hz. As can be observed, magnetic flux density has the greatest magnitude in the E-laminates of the stator and much lower in the rotor. At the higher frequencies the magnetic field is more and more situated in the air, outside the ferromagnetic material.

Fig. 4 represents calculated inductances of the segment model with (w) or without (w/o) the copper layer of the different thicknesses of 0.1 mm, 0.35 mm and 0.5 mm. The results for the ohmic loss in respect to the different copper

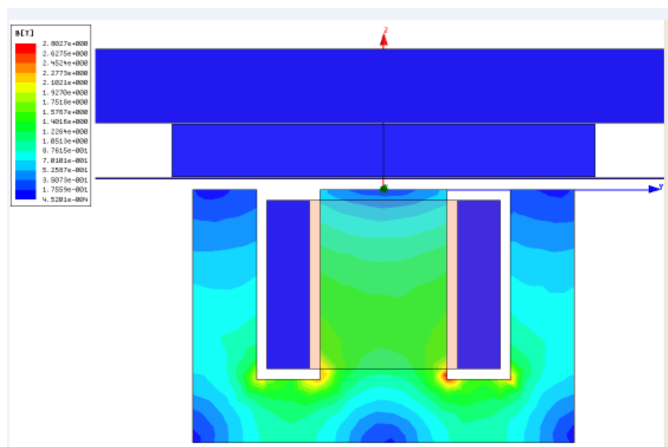

Fig. 3. Calculated values of the magnetic flux density in the model at 50Hz.

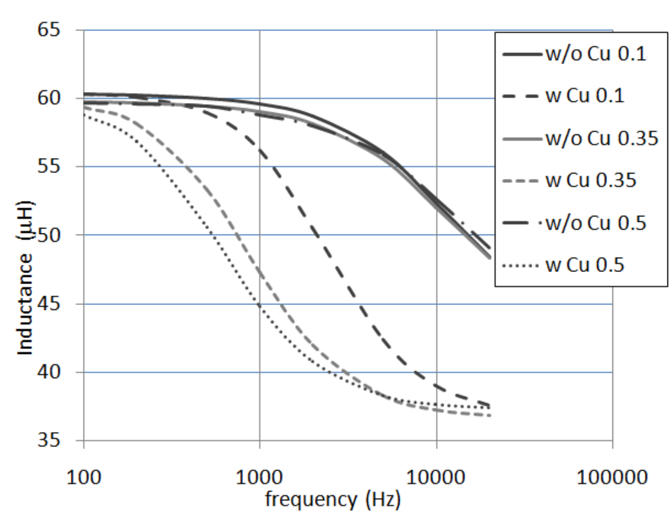

Fig. 4. Calculated values for the inductance of the model.

layer thicknesses are presented in Fig. 5.

Some values of the calculated magnetic force are listed in Table I. The force depends on the relative position of the magnets. For the sake of comparison we present only the results for the central position of the “Stator” between the “Rotor” magnets.

Please notice from Fig. 5 that a thicker layer of the copper shield enables better power loss reduction at high frequencies. In the same time, as observed from Table I, it does not significantly alter the tangential (“y”) component of the magnetic force. The vertical (“z”) component of the force for the segment is visibly reduced. As the BLDC motor torque is controlled by the tangential component only, inserting a thin layer of copper between the stator and rotor should have a little consequence on the torque in a real motor.

IV. Measurement Results

A. The model measurements

The inductance and resistance measurements on the model from Fig. 6 are performed on the HP 4194A Impedance Analyzer. The Figs. 7 and 8 present some of the results for the copper shield thickness of 0.35 mm.

Measured power loss of the model, for the same copper shield thickness of 0.35 mm is presented in Fig. 9. Some results for the different thicknesses are given in Table II. The equipment used for the measurement is the same as used for the motor, described below.

B. The motor measurements

Locked rotor measurements of the power loss and torque produced by the available BLDC motor are performed

TABLE I
Calculated Forces for the Model with the Magnets in the Central Position

Thickness (mm)	Fy (N)	Fz (N)
0.10	4.8	109
0.35	4.6	98
0.50	4.5	93

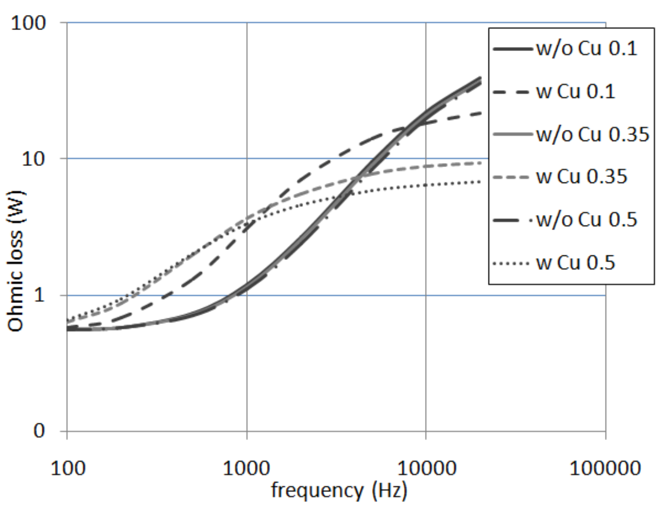

Fig. 5. Calculated values for the power loss in the model.

Fig. 6. Measurements on the model using HP 4194A Impedance Analyzer.

TABLE II
Measured Power Loss in the Physical Model at 22 kHz

Thickness (mm)	Copper layer: Power loss (W)	Plastic layer: Power loss (W)
0.10	35	31
0.35	28	30
0.50	26	29

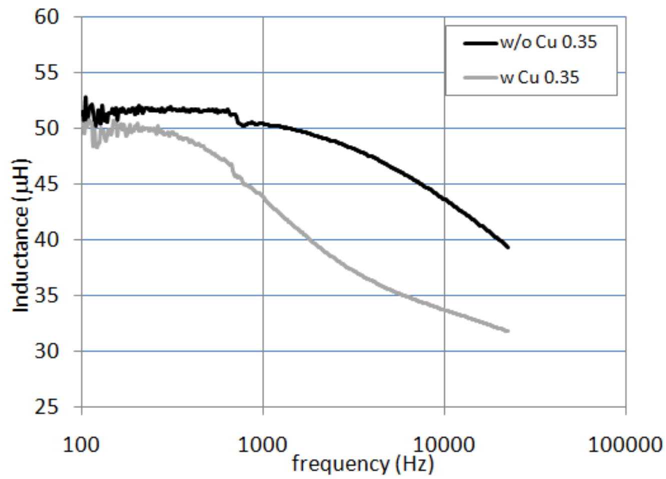

Fig. 7. Measured inductance of the physical model using HP 4194A.

according to the block diagrams from Figs. 10a and 10b. The H-bridge supplies two phases of the motor at time, as is typical with the BLDC drives. The motor terminal voltage is rectangular, with amplitude up to V=40 Vp-p and switching frequency f=22 kHz. The duty cycle varies between 35-65%, to enable the desired average current and the current ripple of approximately 20 Ap-p at the maximum supply voltage. The bridge is supplied by a DC source, signified by Vd in the Figs. 10a and 10b. Total losses of the bridge-motor cascade are measured by an electro-dynamic wattmeter, W, type EL 0120, manufactured by Iskra Co. As the loss of the H-bridge from Fig. 10b is only a small portion of the motor losses, the total losses are attributed to the motor losses.

The H-bridge is built of four MOSFETs, with low channel resistance, R_{DSon}, denoted by Q1-Q4 in Fig.10b. The drive circuits are half bridge drivers of the bootstrap type. The upper and the lower drive channels are controlled by the direct

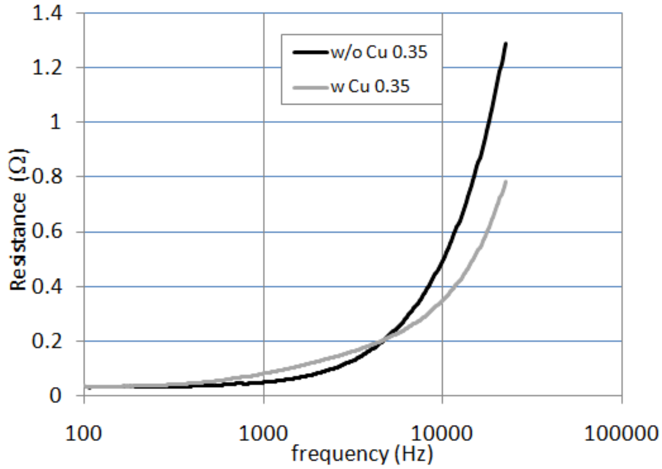

Fig. 8. Measured resistance of the physical model using HP 4194A.

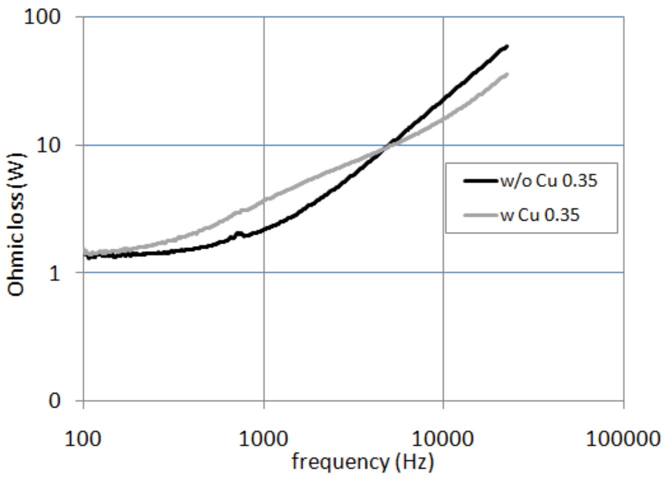

Fig. 9. Measured power loss of the physical model.

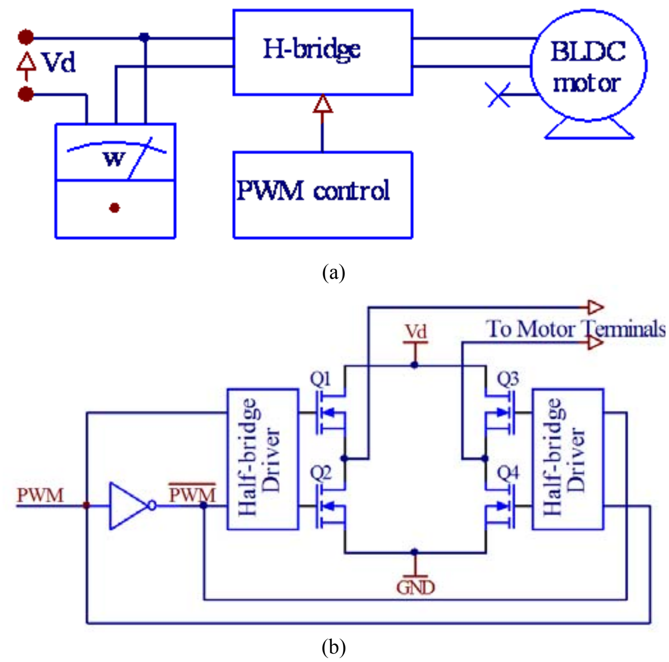

Fig. 10. (a) Diagram of the setup for the BLDC motor measurements, (b) The MOSFET H-bridge with drive circuits and control signals.

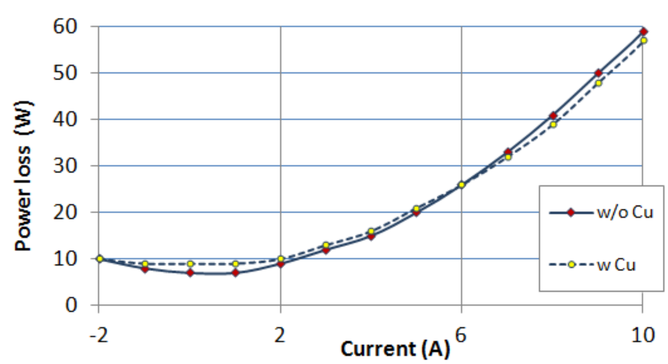

Fig. 11. Measured power loss depending on the average current in the BLDC motor, V=40 Vp-p, f=22 kHz.

and the inverted PWM signals. The bipolar PWM bridge control is achieved by diagonal switching of the transistors, as illustrated in Fig. 10b. The measurement results of the motor loss, with and without the copper layer inserted, are presented in Fig. 11.

Measurements of the physical model power loss are performed with the same equipment from Fig. 10, used for the motor power loss measurements. Some of the results at f=22 kHz, for the voltage V=30 Vp-p, 50% duty cycle and the current ripple about I=20 Ap-p, are summarized in Table II and in Fig. 9.

V. Discussion

As can be seen from Figs. 4 and 7, the results of the inductance calculations and measurements are in reasonably good agreement. The numerical results for the segment's inductance from Fig. 4 suggest that the inductance decays much steeper with the copper layer inserted than without. This can be a desirable feature to enable a fast response BLDC motor current control. Calculated power loss from Fig. 5 is in acceptable agreement with the physical model power measurements from Table II.

As seen from Fig. 11, insertion of the thin copper layer is found to increase the power loss for the smaller average current. For the larger average current, the power loss is slightly reduced in comparison to the no layer situation. Overall, insertion of the copper layer significantly thinner than the skin depth can not be considered beneficial for the motor.

When using ticker copper shield the ohmic losses are visibly reduced. Unfortunately, substantial increase in the copper layer thickness would increase the air gap between the stator and the rotor of a real BLDC motor and would inevitably affect the torque. This effect could not be measured on the model, but is possible to evaluate numerically. Some results are listed in Table I.

VI. Conclusion

The BLDC motor flat segment model is studied in order to explore the influence of the copper thickness on the power loss. 2D numerical analysis of the model was not applicable. Only 3D numerical model gives the results in acceptable agreement with the measurements. Lower ohmic loss is obtained for the copper shied thicknesses comparable to at least one third of the skin depth. As the consequence of the thicker layer inclusion, the air gap between the stator and the rotor must increase. Increasing the gap between the stator and the rotor by a fraction of a millimeter in a real motor, may not reduce the motor torque dramatically, but it is a designer's decision to determine how much torque reduction can be tolerated in return for somewhat lower power loss at the higher frequencies of the motor current.

The BLDC motor losses caused by the supply voltage chopping may be reduced by a highly conductive shield of the appropriate thickness, placed between the stator and the rotor. The shield may be especially effective for the components over 10 kHz, but must have appropriate thickness related to the material skin depth. In the case of the available real BLDC motor measurements, we were limited to evaluate only one, very small thickness for the copper layer. As expected from the calculations and confirmed by the measurements, such layer increases overall ohmic loss for the smaller current magnitudes which is not desirable.

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