Power Losses in Outside-Spin Brushless D.C. Motors

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Abstract. Outside-spin brushless D.C. motors are an alternative to conventional D.C. brush permanent magnet motors, especially in applications that require low power and costs and in which high inertia effects are advantageous. This paper presents a procedure for computing power losses in these kinds of machines. Expressions are derived for predicting copper losses, power interrupter losses, stator iron losses in the tooth and in the yoke, mechanical losses, friction and windage. Stray load losses are also considered and evaluated from previous measurements in outside-spin brushless D.C. motors. The results obtained from the approach proposed are compared to those measured on existing motors, showing a good agreement.

Key words

Outside-spin motors, brushless D.C. motors, copper losses, iron losses, mechanical losses, stray losses, efficiency.

1. Introduction

Outside-spin brushless D.C. motors or brushless D.C. motors with outer rotor have deserved increasing attention in the market of low cost and low power applications that require constant speed, such as motors for fans, motors for office automation (copiers, printers, etc.) and, in general, applications in which high inertia effects are beneficial to the system's performance. These applications, usually powered by permanent magnet D.C. brush motors, demand quieter motors, low EMI levels and require no maintenance. Outside-spin brushless D.C. motors are specially intended for applications that require thin motors (short length and long external diameter). Outside-spin brushless D.C. motors have several advantages over inner-rotor brushless D.C. motors. They have a greater magnet surface, which therefore allows larger airgap and leads to a reduction in mechanical tolerances. In addition, they are less costly to wind. In this paper, a procedure for the determination of power losses in three-phase outside brushless D.C. motors is reported. In this procedure, all kinds of losses (copper, power interrupter, iron, mechanical and stray load losses) are considered and their influence on torque production is studied. This procedure is suitable for design studies that require the fast evaluation of motor performance and in loss evaluation prior to using finite element analysis. The results calculated with the procedure proposed are compared to the experimental results.

2. Drive Description

An outside-spin brushless D.C. motor has an electromagnetic structure, which is formed by an outer rotor that has a permanent magnet arrangement enclosed by soft magnetic steel housing and a stator assembly that consists of a lamination stack with coils wrapped around the stator tooth (Fig. 1). Most of its applications are in the low power (up to 250 W), low voltage (12, 24 V) and moderate speed (slightly over 3000 rpm) ranges. Thin motor design requires a high number of poles to reduce core back iron and end-windings, and that number is only limited by frequency considerations. If good performance and low torque ripple are drive requirements, a three-phase star-connected motor associated with an inverter with six power switches (Power Mosfet, due to the values of voltage and current managed) is the best choice. Usually, three Hall latch sensors are enough for position determination. Low cost requirements mean that ferrite magnets must be used and electric loading must be increased. As a consequence, a large slot area must be adopted. In addition, the power converter and control must find room inside the motor (Fig. 2).

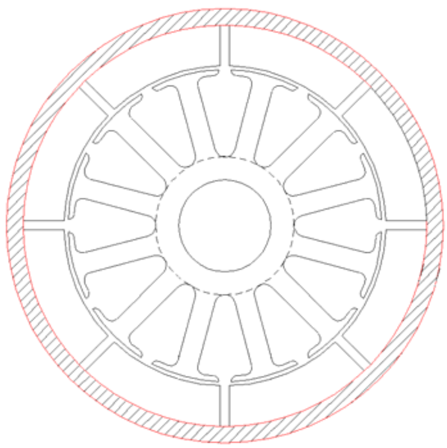

Fig. 1. Cross section of an eight-pole outside-spin brushless D.C. motor

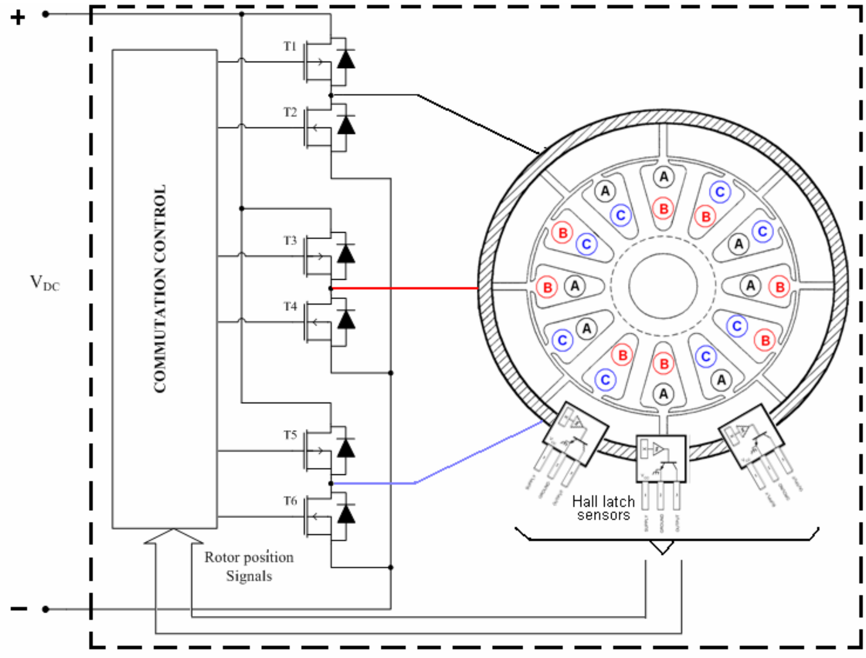

Fig. 2. Block diagram of an outside-spin brushless D.C. motor drive

3. Determination of Power Losses

Power losses in electric motors are an important issue because these losses determine the efficiency of the motor and its heating. High efficiency cuts the operating costs, contributes to energy saving and reduces gas emissions. Moderate heating increases safety. High efficiency in outside brushless D.C. motors can offer a competitive advantage over conventional drives. The following expressions are derived in order to predict copper losses, power interrupter losses, stator iron losses in the tooth and in the yoke, mechanical losses, friction and windage. Stray load losses are also considered and evaluated from previous measurements.

A. Copper Losses

Copper losses at a specified temperature θ are computed by means of the following equation:

$$p_{cu\theta} = 3 k_\theta R_{20^\circ} I_{RMS}^2 \text{ (W)} \qquad (1)$$

where k_θ is the temperature correction factor given by:

$$k_\theta = \frac{235+\theta}{255} \qquad (2)$$

Phase resistance is calculated by means of the expression:

$$R_{20^\circ} = \rho_{20^\circ} \frac{N_f}{s_c} l_{em} \;(\Omega) \qquad (3)$$

where ρ_{20° is the copper resistivity; N_f are the number of turns per phase; s_c is the conductor cross section and l_{em} is the mean coil length.
If we consider, in a first approximation, an ideal 120º square wave, then:

$$I_{RMS} = I\sqrt{\frac{2}{3}} \text{ (A)} \qquad (4)$$

The I flat top current (A) coincides with the D.C. current input. Equation (4) can be substituted in Equation (1) to give:

$$p_{cu\theta} = 2 k_\theta R_{20^\circ} I^2 \text{ (W)} \qquad (5)$$

Skin effects can be neglected because, in outside-spin D.C. motors in the range considered, the skin depth δ is usually higher than the wire size d_c, that is:

$$\delta = \sqrt{\frac{2\rho}{\omega \mu_0}} >> d_c \qquad (6)$$

B. Power Interrupter Losses

If we consider that, in a steady state, there are always two switches in the ON state, the losses across the power interrupters p_{int}, can be evaluated by:

$$p_{\text{int}} = 2 \; R_{ON} \, I^2 \text{(W)} \qquad (7)$$

where R_{ON} is the resistance of the power switch in the ON state.

C. Iron Losses

The specific iron loss for a sinusoidal magnetic field is expressed by means of the well-known Steinmetz equation:

$$P_{Fe} = k_h\, f\, \hat{B}^{\alpha} + k_e f^2\, \hat{B}^2 \,\text{(W/kg)} \quad (8)$$

where the first term is the hysteresis loss and the second is the specific eddy current loss. $\hat{B}$ is the peak value of flux density and β, k_h, α and k_e are constants determined by curve fitting from the manufacturer's data.
The iron loss expression in (8) is only valid for sinusoidal flux density. In brushless D.C. motors, the variation of flux in the stator core is not sinusoidal. Under these conditions, an alternative approach for specific iron loss is given by:

$$P_{Fe} = k_h\, f\, \hat{B}^{\alpha} + \frac{k_e}{2\pi^2}\left(\frac{dB}{dt}\right)^2_{RMS} \text{(W/kg)} \qquad (9)$$

Note that the hysteresis loss term is unchanged as it depends only on the peak value of the flux density, assuming that there are no minor hysteresis loops. By following this approach, expressions for the iron loss are derived in order to predict the hysteresis and eddy current losses in the stator tooth and in the stator yoke, [1] to [4].

1). Iron Losses in the Stator Teeth

Specific iron losses in the teeth p_t , including hysteresis and eddy current losses, can be determined using the following expression:

$$p_t = k_h\, f\, B_t^{\alpha} + \frac{4}{\pi} k_e \frac{f^2\, \hat{B}_t^2}{\alpha_{tt}}\gamma \text{ (W/kg)} \qquad (10)$$

where $\hat{B}_t$ is the teeth flux density and α_{tt} is the augmented tooth arc that can be expressed by:

$$\alpha_{tt} = p\left(\frac{\pi}{s} - \frac{k_c\, w_o}{D}\right) \text{ (elec. rad.)}$$

$$\text{and } \gamma = 1 \quad \text{if} \quad \alpha_{tt} \le \pi - \beta_m$$

$$\text{or} \quad \gamma = \left(2 - \frac{\pi - \beta_m}{\alpha tt}\right) \text{ (elec. rad.)} \quad \text{if} \quad \alpha_{tt} > \pi - \beta_m$$

where s is the slot number, k_c is the Carter coefficient, w_0 is the slot opening and D is the stator diameter.

2). Iron Losses in the Stator Yoke

Specific iron losses in stator yoke p_y , including hysteresis and eddy current losses, can be determined using the following expression:

$$p_y = k_h\, f\, B_y^{\alpha} + \frac{8}{\pi} k_e \frac{f^2\, \hat{B}_y^2}{\beta_m} \text{ (W/kg)} \qquad (11)$$

where $\hat{B}_y$ is the yoke flux density and β_m (elec. rad.) is the magnetic pole arc.

3). Stator Core Loss

The total iron losses p_{Fe} in the stator core, if we ignore surface loss, are calculated by means of the equation:

$$p_{Fe} = p_t\, G_t + p_y\, G_y \text{ (W)} \qquad (12)$$

where p_t and p_y are the specific losses (W/kg) in the teeth and stator yoke and G_t and G_y are the weights (kg) of the tooth and stator yoke respectively.

D. Mechanical Losses [5]

The mechanical losses p_{mec} are subdivided in two parts: friction losses p_{fr} and windage losses p_{wind}:

$$p_{mec} = p_{fr} + p_{wind} \text{ (W)} \qquad (13)$$

Friction losses in bearings can be determined using the following formula:

$$p_{fr} \approx \frac{3}{2}\, n_r\;\; G_{rot}\, N \times 10^{-3} \text{ (W)} \qquad (14)$$

where n_r is the number of bearings, G_{rot} is the rotor weight, and N is the speed (rpm).

Windage losses are evaluated by the formula:

$$p_{wind} \approx 2\, D_{out}^3\, L\, N^3 \times 10^{-6} \text{ (W)} \qquad (15)$$

where D_{out} is the outside rotor's diameter (m), and L is the rotor's length (m).

E. Stray Load Losses

Stray load losses are defined as the losses that arise from the non-uniform distribution of a current in copper. They also encompass additional core losses that are produced in iron by the distortion of magnetic flux by a load current. It is common practice to evaluate stray losses as a percentage (3 to 5%) of the output power of small machines rated up to 10 kW [5]. Nevertheless, several tests performed on outside brushless D.C. motors working at constant speed show that these kinds of losses increase markedly with the load and under these conditions frequency has no influence. In addition, current waveforms are not ideal 120º square waves, which clearly contribute to increasing the amount of copper losses. Therefore, stray load losses can be estimated by means of the following empirical expression:

$$p_s = 2\left(\lambda - \sqrt{\frac{2}{3}}\right) R_{20^\circ}\, I^x \text{ (W)} \tag{16}$$

where $\lambda = \frac{I_{RMS}}{I}$ and is usually between 0.86 and 0.84, and exponent x may be evaluated range from 2.8 to 3.6.

4. Procedure Verification

The proposed procedure for determining power losses is applied to an existing eight-pole outside-spin brushless D.C. motor (Table I). The computed power losses are compared to the data tested. From a non-load test at different speeds, the stator core, windage and friction losses are obtained (Fig. 3). From a load test, in which the outside-spin brushless D.C. motor is connected to a dynamometer, efficiency versus load is reported (Fig. 4).
Very good agreement is derived from the non-load test; therefore, the computation of stator core and mechanical losses based on the expressions proposed is suitable for this kind of motor. The efficiency calculated under different load conditions shows significant variations at loads lower than 0.5 p.u., compared to values obtained experimentally, although there is fairly good agreement in the range of 0.5 p.u. to 1.25 p.u.

TABLE I. - Main Characteristics of an Eight-Pole Outside-Spin Brushless D.C. Motor

Voltage	12 V
Torque	20 Ncm
Current	7 A
Speed	2500 rpm
Output diameter	95 mm
Total length	40 mm
Permanent magnets	Ferrites FXD 4 A Br =415 mT
Lamination	M-600-65 A

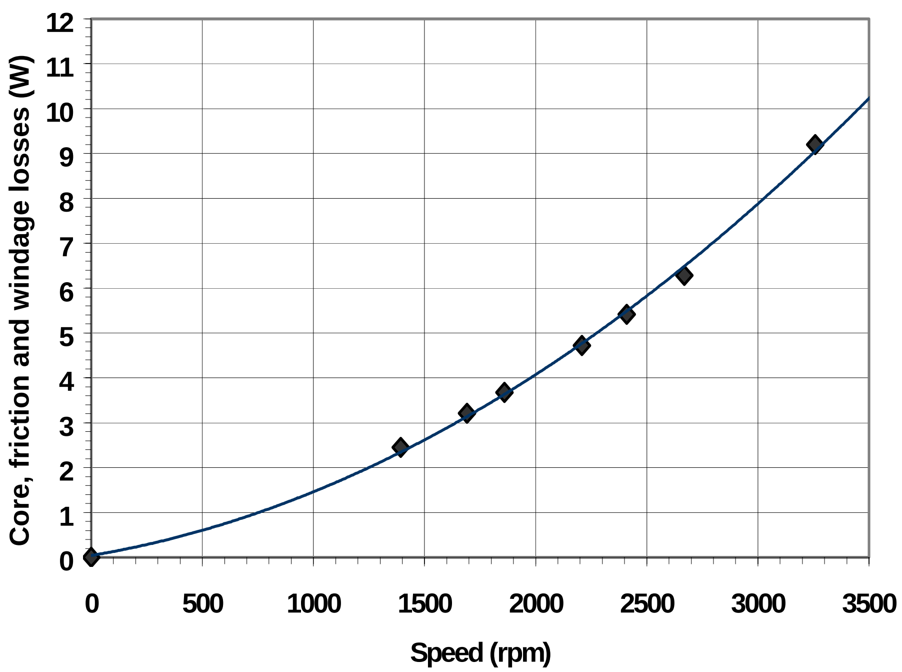

Fig. 3. Core friction and windage losses versus speed. The straight line was obtained using the expressions proposed, and the points were obtained experimentally

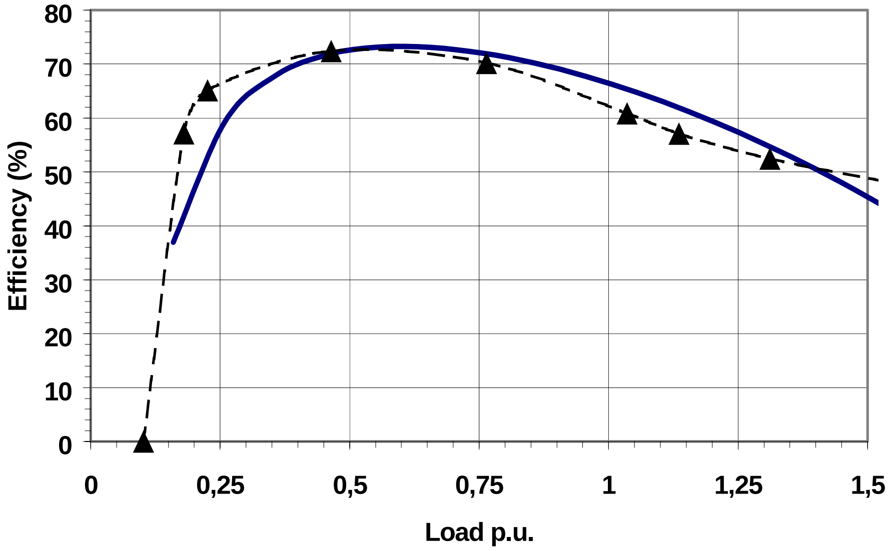

Fig. 4. Efficiency (%) versus load (p.u.). The straight line was obtained using the expressions proposed, and discontinuous line shows the experimental results

5. Conclusions

The paper describes a procedure for power loss determination in outside-spin brushless D.C. motors. In the procedure proposed, expressions are derived for predicting copper losses, power interruption losses, stator iron losses in the tooth and in the yoke, mechanical losses, friction and windage. Stray load losses are also considered and evaluated from previous measurements. Power loss determination using the methodology explained show good agreement with the experimental results obtained from the tests. The procedure proposed is suitable for design studies that require a fast evaluation of motor performance and in loss evaluation prior to using finite element analysis.

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