Investigation on the relationship between winding wire size and total loss of BLDC

Jinshun Hao¹, Shuangfu Suo²,*, Yiyong Yang¹, Yang Wang¹ and Wenjie Wang²

¹School of Engineering and Technology, China University of Geosciences, Beijing 100083, China
²State Key Laboratory of Tribology, Tsinghua University, Beijing, 100084, China

*Corresponding author: sfsuo@mail.tsinghua.edu.cn

Abstract. The wire size has a significant influence on the total loss of BLDC. In order to determine the relationship between the wire size and the total loss, and to find the wire size which minimizes the total loss of BLDC, this paper proposes a method based on wire diameter to calculate the total loss, and the finite element method is used to verify it. Using this method to analyse a motor model, it is found that with the increase of wire diameter, the total loss of BLDC shows a trend of decreasing and then increasing, and there is a wire size which minimizes the total loss of BLDC.

1. Introduction

Because of high power density and excellent speed performance, BLDC has been used in many areas[1]. But at this stage, in some special applications, such as aerospace, robotic drive and other conditions, higher power density is required. However, increasing power density will inevitably lead to the rise of motor temperature, and the temperature rise of the motor is one of the main factors which restrict the increase of motor power density [2].

Researchers have done extensive researches on the temperature rise and found that measures for solving the problem are mainly divided into two categories: 1. Improving the cooling capacity of the motor; 2. Reducing the losses of the motor.

In terms of improving the cooling capacity of the motor: a thermal-transfer structure based on the heat pipe has been proposed, which can increase the heat dissipation area of the motor and then promote motor cooling [3]; some nozzles are used in a permanent motor to cool the stator end windings [4]. And in the slots of motors which use flat wires, some space is available and used as water channel to cool the coils [5].

In terms of reducing motor losses: some attempts have been made to optimize the slot/pole ratio to reduce losses of motors [6-7]; and some new control methods have been proposed to improve the motor efficiency [8-9].

However, the research of motor loss reduction at this stage mainly focuses on the optimization of the slot/pole ratio and control methods, and no attention has been paid to the influence of the winding diameter on BLDC losses. It can be known from basic formulas of the BLDC that while keeping the slot fill factor and the rated power constant, the change of wire size will influence winding resistance and then affect the copper loss; meanwhile the rated speed will change and then influence the core loss.

In this paper, a method based on wire diameter to calculate the total loss of BLDC was proposed. By comparing the total losses of BLDC with different wire sizes, the wire size which minimizes total...
loss can be found. And the proposed method is verified by the finite element method with a constant rated power BLDC.

2. Mathematical model

2.1 Model solution method

For a BLDC with reference wire, Maxwell is used to model and analyse it to obtain the data of copper loss and magnetic field change, and then, according to the data of the magnetic field, the core loss can be obtained by taking Bertotti’s core loss model, thereby obtaining the total loss of the motor (copper and core). As shown in Figure 1, for the motor with a comparative wire diameter, the copper loss and rotating speed can be obtained by “wire size-copper loss formula” and “wire size-speed formula”, and combined with the magnetic field change of the motor with reference wire, the core loss can be calculated; then, the total loss is obtained. Comparing the calculations, the best wire diameter that can minimize the total loss of the BLDC can be obtained.

2.2 Wire size-speed formula

First, it is assumed that the slot full factor T is constant when the BLDC uses different wire sizes.

\[ T = \frac{nd^2}{S} \]  \hspace{1cm} (1)

- \( n \) — conductors per slot
- \( d \) — wire size
- \( S \) — slot area

Set \( d_0 \) as reference wire size, and \( d_i \) as the size of the wire numbered \( i \), then:

\[ x = \frac{d_i}{d_0} \]  \hspace{1cm} (2)

Set \( L_i \) be the cross-sectional area of the wire numbered \( i \), then:
\[ \frac{A_i}{A_0} = x^2 \] (3)

Since the slot fill factor \( T \) is constant, the total volume of armature windings in slots is constant. Therefore:

\[ \frac{L_i}{L_0} = \frac{1}{x^2} \] (4)

\( L_i \)—— The total length of the effective conductor when the wire is numbered \( i \)

However, due to the limitation of the wire size, different specifications of wire can only achieve similar slot fill factor; taking this factor into consideration, let:

\[ K = \frac{T_i}{T_0} \] (5)

Solve Equations (2), (3), (4) and (5) simultaneously:

\[ \frac{L_i}{L_0} = \frac{K}{x^2} \] (6)

At the same time, ignoring the armature reaction, let the rated power \( P \) of the BLDC is constant when the wire size changes, there are:

\[ P = B I_0 L_0 v_0 = B I_i L_i v_i \] (7)

\( B \)—— Air gap flux density(T)

\( v \)—— Rotor line speed(m/s)

\( I_i \)—— Armature current with winding numbered \( i \) (A)

Solve Equations (6) and (7) Simultaneously:

\[ (I_0 v_0) \frac{x^2}{K} = I_i v_i \] (8)

At the same time, the armature current calculation formula is:

\[ I = \frac{U - B L v}{R} \] (9)

\( U \)—— Voltage(V)

\( R \)—— Armature resistance(ohm)

Solve Equations (8) and (9) Simultaneously:

\[ v_i = \frac{x^2 U + \sqrt{(x^2 U)^2 - 4B L_0 v_0 K (U - L_0 v_0)}}{2 B L_0 K} \] (10)

From (10), when the rated speed of the motor with the wire size \( d_0 \) is known as \( v_0 \), and the slot full factor remains basically unchanged, \( v_i \) can be obtained, and both motors have the same rated power.

2.3 Wire size-copper loss formula

The formula for the wire resistance \( R \) is

\[ R = \rho \frac{L}{A} \] (11)
\[ \rho \quad \text{Specific resistance} \]
\[ L \quad \text{Conductor length} \]
\[ S \quad \text{Conductor cross-sectional area} \]

Solve Equations (3), (6) and (11) Simultaneously:

\[ P_{\text{cu}} = P_{\text{cu0}} \left( \frac{V_i}{V_j} \right)^2 = \]
\[ P_{\text{cu0}} \left( \frac{2BLnV_0}{x^2U + \sqrt{(x^2U)^2 + 4BLnV_0K(U - BLnV_0)}} \right)^2 \quad (12) \]

From (12), if the rated power and slot full factor keep constantly, the copper loss \( P_{\text{cu}} \) can be obtained when wire size \( d_i \) varies.

2.4 Core loss calculation

Regarding the calculation of motor core loss, researchers at this stage generally adopted the core loss solution model proposed by Bertotti[10] in 1988:

\[ \begin{align*}
P_{Fe} &= P_h + P_e + P_{ex} \\
\quad P_h &= K_hf^2B_m^b \\
\quad P_e &= K_ef^2 \int_0^{2\pi} \left( \frac{dB(\theta)}{d\theta} \right)^2 d\theta \\
\quad P_{ex} &= K_{ex}f^{1.5} \int_0^{2\pi} \left| \frac{dB(\theta)}{d\theta} \right|^{1.5} d\theta (13)
\end{align*} \]

Since the above core loss model is based on the permanent magnet synchronous motor, the condition is that the magnetic density changes sinusoidally. However, the magnetic density change of the BLDC is close to the square wave. Therefore, the researchers now mainly use the orthogonal decomposition-Fourier decomposition to process the change data of the magnetic density of the BLDC, and then use the above core loss calculation model to solve the core loss[11-12]: firstly, the BLDC magnetic density is decomposed into Bt and Br in the tangential and normal direction; secondly, Bt and Br are subjected to Fourier decomposition; and then the decomposed results are substituted into the above core loss solving model to calculate the core loss:

\[ P_{Fe} = \sum_{i=1}^n \left( K_hfB_{ymi}^b + K_e f^2 B_{ymi}^2 + K_{ex} (fB_{ymi})^{1.5} \right) + \]
\[ \sum_{j=1}^m \left( K_h fB_{ym}^b + K_e f^2 B_{ym}^2 + K_{ex} (fB_{ym})^{1.5} \right) \quad (14) \]

When using the above model to calculate the core loss of the BLDC, a complete stator tooth is first selected and divided into three parts: the yoke, the tooth body and the tooth top. Some points are evenly selected in each part and the core loss value of each point is calculated. Then the average core loss of the points in each area replace the average core loss in each area to calculate the core loss. The locations of three parts and the points are shown in Figure 2.
In this paper, for the BLDC with the reference wire size, the magnetic density change of each point which is obtained by Maxwell's analysis at rated speed is substituted into the formula (14) to calculate the motor core loss. Meanwhile, motor speeds calculated by formula (10) and the magnetic density change data of the BLDC with reference wire are used to calculate the core loss of BLDC with comparative windings.

3. Comparison of motor losses

3.1 Motor model
The quantitative analysis between wire size and losses is based on an existing BLDC, and Table 1 shows the main parameters of the motor.

| Motor parameter         | Value          |
|-------------------------|----------------|
| Rated power             | 4000W          |
| Rated voltage           | 270V           |
| Stator outer diameter   | 160mm          |
| Pole/slot               | 16/18          |
| Slot full factor        | 70.4%          |
| Stator material         | 3WW250         |
| comparative wire sizes  | 1.938, 1.829,  |
| (mm)                    | 1.628, 1.537,  |
| Reference wire size     | 1.725mm        |

3.2 Comparison of results
The copper losses of the BLDC are calculated by finite element method and formula (12). As shown in Figure 3: the results obtained by the two methods are well fitted, and the copper loss decreases gradually with the increase of wire diameter.
Figure 3. Copper loss calculated by different methods

Two different methods are used to calculate the core losses of the motors: (1) Maxwell software is used to model and analyze the BLDC with the reference wire and comparative wires, so as to obtain the rated speeds as well as the changes of magnetic density of the selected points on a complete tooth, and then the core losses are calculated based on formula (14); for the motor with reference wire, core loss is calculated based on the method(1); meanwhile, for the BLDC with comparative wires, rated speeds are calculated based on formula(10), then the speeds as well as the magnetic field data of the BLDC with reference wire are used to calculated core losses based on formula(14). As shown in Figure 3: the results calculated by the two methods are in good agreement with each other; and with the increase of wire size, the core loss increases gradually.

Figure 4. Core loss calculated by different methods

Total loss $P_{\text{loss}} = P_{Fe} + P_{cu}$, and as shown in Figure 4: the difference between the results obtained by the formula method and the finite element method is not more than 1.5%; in addition, with the increase of the wire diameter, the total loss of the BLDC first decreases and then increases; and for a BLDC, there is a wire size which minimizes the total loss of it; for the BLDC in this paper, the wire size is 1.628 mm.
4. Conclusions
In this paper, a method for quickly finding the wire size which can minimize the total loss of the BLDC is proposed: with this method, total losses of BLDC can be calculated quickly; by comparing these data, it is possible to quickly find the best wire size, thereby reducing the heat dissipation pressure of the BLDC, and helping to further increase the BLDC power density.

In addition, this paper analyzes the motor model and finds:
1) With the increase of wire size, the copper loss of BLDC gradually decreases, and the core loss gradually increases;
2) With the increase of wire size, the total loss of BLDC shows a trend of decreasing and then increasing.
3) For a BLDC, there is a wire size which minimizes the total loss of it.

References
[1] G. Suresh Babu, M. Murali Krishna, B. Vikram Reddy, EPES, 4, 9 (2015)
[2] M. Zhang, Doctoral dissertation, NWPU (2016)
[3] L. Li, J. Zhang, C. Zhang, J. Yu. TAS, 26 (2016)
[4] A.M. EL-Refaie, J. Alexander, S. Galioto, P.B. Reddy, K.K. Huh, P. Bock, X. Shen, Industry Applications IEEE Transactions on, 50, 3235 (2014)
[5] M. Schiefer, M. Doppelbauer. IEMDC, 1820 (2016)
[6] Y. Fu, M. Takemoto, S. Ogasawara, K. Orikawa, JEMDC, 1 (2017)
[7] L. Yu, Y. Rui, J. Sun. MET, 41, 166 (2018)
[8] G. Jie, W. Ma, J. Geng, Z. Nei, H. Wu, Proceeding of the CSEE, 26, 131 (2006)
[9] J. Zhao, B. Tan, L. Ding, P. Qu, MET, 41, 147 (2018)
[10] G. Bertotti. IEEE Transactions on Magnetics, 24, 621 (1988)
[11] Y. Huang, Q. Hu, J. Zhu, EMCA, 34, 6 (2007)
[12] W. Zhang, Y. Wan, Q. Wang, K. Cao, J. Hu, MICROMOTORS, 49, 17 (2016)