Hysteresis Torque Estimation Method Based on Iron-Loss Analysis for Permanent Magnet Synchronous Motor

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In the design process of permanent magnet synchronous motors (PMSMs), the hysteresis torque has so far been ignored under the understanding that it is already small enough. However, for some delicate applications, such as an exoskeleton wearable robot, the hysteresis torque, whose proportion increases under no-load or low-load conditions, needs to be further minimized even though the hysteresis torque has low magnitude. Conventional methods using hysteresis models to calculate the hysteresis torque require a lot of computation resources. Therefore, this paper proposes a simpler method in order to estimate the hysteresis torque using iron-loss experimental data. In the proposed method, the hysteresis torque is derived from the hysteresis loss, which is separated from the iron-loss experimental data by using the modified Steinmetz equation. Finally, the hysteresis torque of the proposed surface-mounted PMSM is measured via experiments to verify the validity of the proposed method. The hysteresis torque is obtained by subtracting the mechanical friction torque from the no-load offset torque. The experimental result is compared with the results obtained from the proposed method.

***Index Terms*—Exoskeleton wearable robot, hysteresis torque, iron-loss separation, no-load torque, permanent magnet synchronous motor (PMSM).**

I. INTRODUCTION

THE requirement of high torque density and precise controllability of electric motors has made permanent magnet synchronous motors (PMSMs) more and more popular in many industries. The presence of permanent magnets results in torque pulsation under no-load conditions, which consists of cogging torque and offset torque, the sum of the friction torque and the hysteresis torque. The hysteresis torque has generally been ignored so far, because of its low magnitude, while studies on cogging torque reduction have been carried out with great enthusiasm. However, in some cases, the characteristics of the torque under no-load or relatively very low-load conditions are very important according to the applications of the motors. For high precision machines, not only cogging torque reduction but also the hysteresis torque minimization is required even though the cogging torque is larger than the hysteresis torque.

The exoskeleton wearable robot helps the motion of weak people by boosting up torques at each joint using the electric motors. However, in the opposite sense, the motor can generate torque reverse to the user's intended motion. For example, when the users want to lower their arms, the electric motor does not have to boost the motion. At this point, in order not to disturb the user's motion, the torque under no-load conditions should be minimized.

In order to reduce the hysteresis torque, it is necessary to estimate the hysteresis torque in the design process of motors for exoskeleton wearable robots. The conventional method for calculating hysteresis torque is to use the Preisach model [1], [2]. However, this model requires a vast amount of computation resources and time. Thus, a prior paper proposed a simpler and faster method based on the iron-loss experimental data [3]. Unfortunately, it ignores the eddy current loss and the anomalous loss regarding total iron loss as hysteresis loss at low frequencies. Thus, the hysteresis torque can be estimated more precisely by considering the eddy current loss and the anomalous loss in the magnetic core of the motors. By estimating the hysteresis torque simply and accurately, the hysteresis torque reduction process can be conducted more easily.

In this paper, for a more accurate estimation of the hysteresis torque, the hysteresis loss will be separated from the total iron-loss experimental data by using a modified Steinmetz equation. The modified Steinmetz equation is composed of three terms: the hysteresis loss, the eddy current loss, and the anomalous loss. Because these three terms are independent in the equation, terms of the eddy current loss and the anomalous loss can be simply eliminated. To conduct the loss separation, therefore, the iron-loss curve should be obtained first. In this paper, several iron-loss curves according to the target frequencies are obtained, respectively, to minimize the chance of errors. Thus, to find the curves, the iron-loss experimental data are interpolated by using the modified Steinmetz equation. During this process, each curve is interpolated, respectively the experimental data at two adjacent frequencies to the target frequency. Consequently, more accurate results of the iron losses at each target frequency can be obtained than the results that are interpolated to the loss of all frequency ranges at once. To verify the validity of the proposed method, the surface-mounted PMSM (SPMSM) for an exoskeleton wearable robot application will be presented as an analysis model. Under the no-load condition, the hysteresis torque of the motor will be measured experimentally for several target frequencies. Finally, it will be compared with the estimation value obtained from the proposed hysteresis torque estimation method.

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II. BACKGROUND

A. Generation of Hysteresis Torque

The mechanism of the hysteresis torque generation is graphically shown in Fig. 1. When the magnetic field is induced

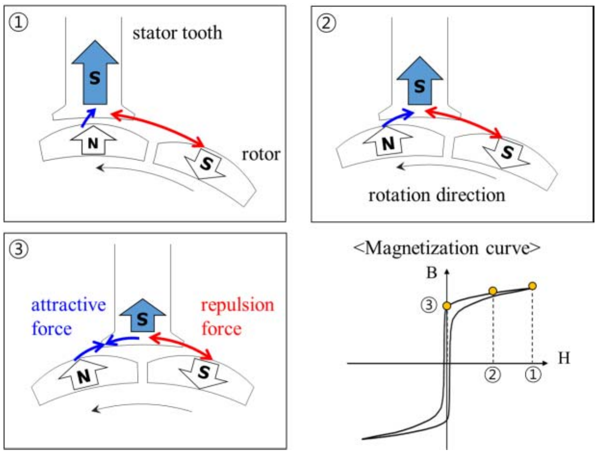

Fig. 1. Mechanism of hysteresis torque generation.

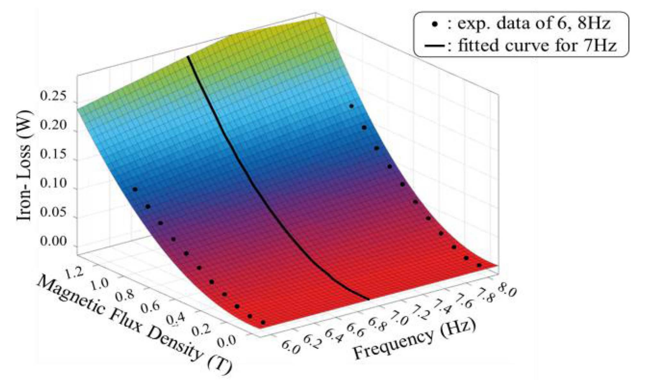

Fig. 2. Iron-loss fitting at 7 Hz with the experimental data of 6 and 8 Hz.

by the permanent magnets of the rotor, the stator core tooth is magnetized. The magnetic flux density B of the tooth is determined by the induced magnetic field intensity H. The relationship between them is described by the magnetization curve of a core material, which is dependent on the operating frequency, as shown in Fig. 1. It can be seen that there is a time lag between the magnetic field intensity H and magnetic flux density B in the stator core tooth. When the rotor is located at position 1, the stator core tooth is fully magnetized because the tooth is located at the center of the permanent magnet. As the rotor rotates counterclockwise to position 2, the magnetic flux density of the tooth slightly decreases but remains magnetized at the same polarity. Therefore, an attractive force acts in between the leaving permanent magnet and tooth, and a repulsion force acts in between the permanent magnet and tooth. Both forces are opposite to the rotation direction. This phenomenon occurs on all the teeth in the same way at all positions in the rotor. This resistive torque generated by the hysteresis phenomenon of the iron core is called hysteresis torque. With the hysteresis loss which will be calculated by iron-loss analysis in the next step, the hysteresis torque can be calculated by the following equation:

$$P_{\text{hysteresis}} = T_{\text{hysteresis}} \cdot \omega \tag{1}$$

where P represents for loss in W, and T and ω are torque in Nm and angular velocity of the rotor in rad/s, respectively.

B. Hysteresis Loss Separation

The iron loss is generally described as the modified Steinmetz equation as follows [4], [5]:

$$P_{\text{iron-loss}} = k_h f B^2 + k_e f^2 B^2 + k_a f^{1.5} B^{1.5} \tag{2}$$

where f and B are the operating frequency and magnitude of the magnetic flux density, and k_h, k_e, and k_a are the coefficients of the hysteresis loss, eddy current loss, and anomalous loss, respectively. Indeed, it has been discovered that the orders of magnetic flux density of each loss differ according to the material [6]. However, the general equation is adopted in this paper [7]. The coefficients can be determined by fitting a curve of the equation to the iron-loss experimental data. Those iron-loss coefficients, however, are not constant but rather they vary when the frequency differs. Therefore, coefficients need to be explained as the functions of frequency. However, fitting a curve using the iron-loss coefficients for a wide range of frequencies at once is prone to leading to a greater possibility of errors in the estimated iron loss.

In this paper, in order to minimize the cause of errors, the sets of iron-loss coefficients at each target frequency are obtained by using the experimental data at two adjacent frequencies. One is higher and the other is lower than the target frequency. By interpolating a curve with the experimental data of the two frequencies, the curve can be closer to the experimental data than the curve which is interpolated with the experimental data of all frequencies at once.

Consequently, at each of the target frequencies, the hysteresis loss separation will be conducted by using the interpolated iron-loss curves. Through this process, the iron-loss surface between 6 and 8 Hz can be obtained, as shown in Fig. 2. In Fig. 2, the iron-loss experimental data at 6 and 8 Hz are presented as black dots. The estimated iron loss at 7 Hz is presented by a black line. With the obtained iron-loss coefficients, the hysteresis loss can be obtained by using (3), which is separated from (2)

$$P_{\text{hysteresis}} = k_h f B^2. \tag{3}$$

Then, the hysteresis torque according to the speed can be calculated via (1).

C. Offset Torque Measurement

When the torque of PMSMs under no-load conditions is measured, the average of the fluctuation is not zero but there is an offset. The major of the torque pulsation under no-load conditions is the cogging torque; however, the offset cannot be ignored for specific applications. The total offset torque consists of the mechanical friction torque and the hysteresis torque, as shown in Fig. 3 [8]. It is not the real waveform of the tested motor in this paper but instead a conceptual graph that describes the general composition of the no-load torque of the PMSM. Even though the hysteresis torque and the friction torque fluctuate slightly as the rotor rotates, the average values of the torques are used in this paper, as shown in Fig. 3. The mechanical friction torque can be obtained by measuring the torque of a motor with a non-magnetized rotor or a motor without a stator iron core. It means that the interaction between

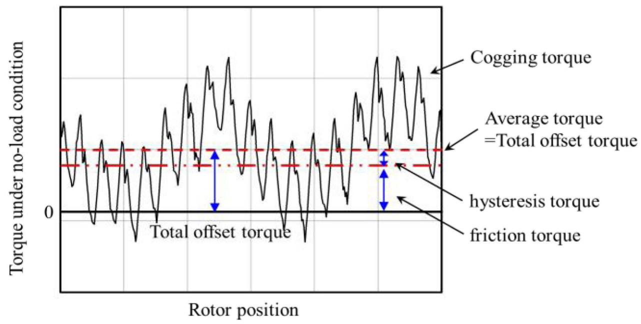

Fig. 3. General composition of torque under no-load conditions of PMSM.

Fig. 4. SPMSM designed for exoskeleton wearable robots.

TABLE I
MOTOR SPECIFICATIONS

Items	Unit	Value
Number of poles	-	14
Number of slots	-	18
Core material	-	20PNF1500 (POSCO Electrical Steel)
Stack length	mm	7
Outer diameter	mm	75
Rated torque	Nm	0.4
Rated speed	RPM	5500
Rated power	W	230

the magnetic field and the iron core, which leads to the iron loss, never occurs. As a result, the hysteresis torque can be obtained by subtracting the measured mechanical friction torque from the measured total offset torque.

III. VALIDATION

A. Analysis Model

The 14-pole 18-slot SPMSM as an analysis model is shown in Fig. 4 to examine its hysteresis torque. It is designed for the joints of an exoskeleton wearable robot. In order to minimize the hysteresis loss, the designed shape of the magnetic core has minimum magnetic resistance, and the saturation is well balanced. In addition, the 20PNF1500 (POSCO Electrical Steel), whose iron loss is very low, is selected as the core material of both the stator and the rotor. The specifications of the motor are shown in Table I.

B. Hysteresis Torque Analysis

Iron-loss experimental data are obtained by the Epstein test method based on the standard IEC 60404-02. Taking into consideration the data sampling period of the experimental

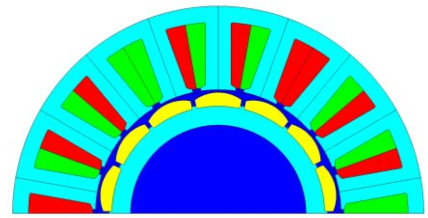

Fig. 5. 2-D FEA model of SPMSM designed for exoskeleton wearable robots.

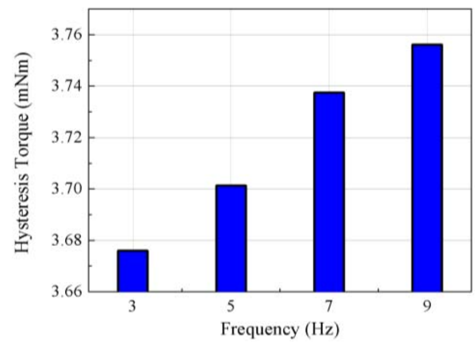

Fig. 6. Analyzed hysteresis torque under no-load conditions.

system, target frequencies are determined at 3, 5, 7, and 9 Hz. The iron-loss data at 2 and 4 Hz are used to interpolate the hysteresis loss at 3 Hz by using the modified Steinmetz equation. Through the same method, the iron-loss data at 4 and 6 Hz, 6 and 8 Hz, and 8 and 10 Hz are used to interpolate the loss at 5, 7, and 9 Hz, respectively. Then, using the hysteresis loss separation method, the hysteresis loss of the core material at each of the frequencies can be obtained.

To analyze the hysteresis torque of the motor, the obtained hysteresis loss of the core is applied in the process of the numerical method using the 2-D finite-element analysis (FEA) model, as shown in Fig. 5 [9], [10]. The non-linear 2-D FEA is conducted under no-load conditions at the target frequencies, and the hysteresis losses are analyzed. The results are used to calculate the hysteresis torque using (1). The estimation result of the hysteresis torque is shown in Fig. 6. It can be seen that the hysteresis torque rises linearly as the frequency increases, as shown in (2).

C. Hysteresis Torque Measurement

In order to verify the validity of the proposed method, the experimental system for the proposed SPMSM as the test motor is set up, as shown in Fig. 7, the used torque transducer is SETECH YDSA-20KC, and its capacity is 1.961 Nm with 0.2% reliability. Under the no-load conditions, the drive motor rotates the test motor at the speed of the target frequency. When they rotate under the steady-state region, the torque is not zero because of the mechanical friction torque and the hysteresis torque. Therefore, the torque transducer transmits the signal to a computer which then stores the measured torque data.

To calculate the hysteresis torque of the proposed motor, two different tests should be conducted. First, the torque of the test motor without the stator core at the target speed is measured for 10 seconds with a 500 Hz sampling frequency,

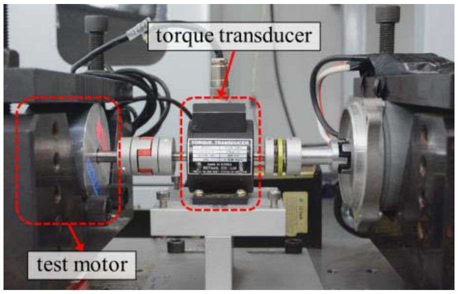

Fig. 7. Torque measurement system.

TABLE II
MEASURED TORQUE WITH AND WITHOUT STATOR CORE

Frequency (Hz)	Measured Torque (mNm)	
	with stator core	without stator core
3	26.340	22.909
5	29.313	25.725
7	24.574	21.497
9	23.312	20.019

TABLE III
COMPARISON BETWEEN ANALYZED AND MEASURED HYSTERESIS TORQUE

Frequency (Hz)	Hysteresis Torque (mNm)		
	Measurement	Analysis	Error (%)
3	3.431	3.676	7.13
5	3.588	3.701	3.15
7	3.077	3.737	21.45
9	3.293	3.756	14.06

and the average value is used. Then, the torque of the test motor with the stator core is measured through the same method. The measurement was conducted six times with and without the stator core. The maximum and minimum values were excluded, and the average of the four values was used as the measured values. This method removes the effect of the cogging torque and the mechanical unbalance of the system, and increases the precision of the experimental results. Finally, the hysteresis torque can be obtained by subtracting the measured torque without a stator core from the measured torque with a stator core.

The experimental results are shown in Table II and are compared with the analyzed hysteresis torque obtained via the proposed method in Table III. The result shows that the error between them is only 0.113–0.66 mNm. Therefore, it is concluded that the proposed method in this paper is useful to estimate the hysteresis torque in a simple way.

IV. CONCLUSION

The hysteresis torque estimation method for PMSMs is proposed based on the iron-loss experimental data and modified Steinmetz equation in this paper. It is a simpler way than the general method which uses the hysteresis models. By using the equation, the iron-loss data of two frequencies, one higher and the other lower than the target frequency, are used to interpolate the losses around the target frequency. With the interpolated equation, the hysteresis loss can be separated from the interpolated equation. By dividing the hysteresis loss by the rotational speed, the hysteresis torque can be obtained. In order to verify the validity of the proposed method, the hysteresis torque of the proposed SPMSM for exoskeleton wearable robots is measured. Under the no-load conditions, the torque of the motor with and without its stator core is measured. By subtracting the friction torque from the no-load torque, the experimental hysteresis torque can be obtained. Finally, the hysteresis torque obtained from the proposed method is compared with that of the experimental method at four target frequencies. The results show that the proposed method can be used in the design process of the PMSM as a simple method to estimate the hysteresis torque.

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