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Review Article

Hysteresis Loop Measurement for Steel Sheet under PWM Excitation Condition

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Abstract

This article adopts a method of measuring the hysteresis loop of oriented silicon steel sheet under the excitation of pulse width modulation (PWM) signal. A measurement platform was built on the basis of the traditional Epstein frame method. According to international standards, the length of the equivalent magnetic circuit of the Epstein frame was calculated, and the harmonic control method was used to achieve the measurement of the hysteresis loop of the oriented silicon steel sheet under PWM excitation. Starting from the traditional sinusoidal excitation, this paper measures the variation of the hysteresis loop of the silicon steel sheet under different frequency excitation. On this basis, the waveform control and PWM signal output programming were carried out through the host computer, and the influence of high-order harmonics of different frequencies on the magnetic properties of the oriented silicon steel sheet under PWM excitation was compared. Provide theoretical basis for the design and research of transformer laminated core.

Keywords: Pulse Width Modulation; High-order Harmonics; Hysteresis Loop

Introduction

The laminated core has become a widely used magnetic circuit component in power transformers. The analysis of the magnetic field problem in the laminated core and the optimization of its structure are key issues in the design of power transformers. With the rapid development of power electronics technology, PWM technology widely used in modern electric drive systems. Compared with the traditional sinusoidal power supply, due to the rich high-order harmonics in voltage and current, the loss in the iron core of electrical equipment will increase significantly. According to the relevant standards of magnetic property measurement, the existing electrical steel sheet manufacturers only provide the magnetic property measurement data under the excitation of standard sinusoidal magnetic flux density. These data cannot accurately characterize the magnetic properties of electrical steel sheets under complex conditions [1]. In order to accurately evaluate and take effective measures to reduce core loss and improve the energy efficiency of electrical equipment in the design stage, it is necessary to accurately measure the hysteresis loop of electrical steel sheet under the excitation of Pulse Width Modulation (PWM) power supply [6].

So far, domestic and international standards for measuring the magnetic properties of electrical steel sheets under the excitation of sinusoidal magnetic flux density have been published. Because the measurement of the magnetic properties of electrical steel sheets under PWM excitation is related to many factors, and each influencing factor is coupled with each other, there are few reports on related measurement standards. Literature [4] proposed the possibility of establishing a standard method for measuring the magnetic properties of soft magnetic materials under inverter power supply, discussed its influencing factors. Literature [5] uses Epstein frame to develop an automatic test system under PWM excitation mode, derives the analytical expression of the iron loss measurement error, and points out that the phase difference of the signal is a key factor affecting the measurement accuracy. After calibration, Repeatability is within 3%. Literature [2] uses a single-sheet tester method, considers the influence of harmonics on magnetic characteristics, determines the selection method of the reference waveform, controls the excitation waveform, and obtains the core data under PWM excitation. Literature [8] measured the magnetic characteristics of the toroidal core of a high-frequency transformer under PWM excitation, and constructed a core loss calculation model.

In this paper, based on the original Epstein frame measurement standard, by improving the experimental platform and measurement system, a measurement system for the magnetic properties of electrical steel sheets under PWM excitation is built. The hysteresis loop of 30QG120 grain-oriented electrical steel sheet under PWM power supply was measured, and the influence of high-order harmonics on the hysteresis loop of grain-oriented silicon steel sheet was studied.

Experimental device

Epstein frame parameters

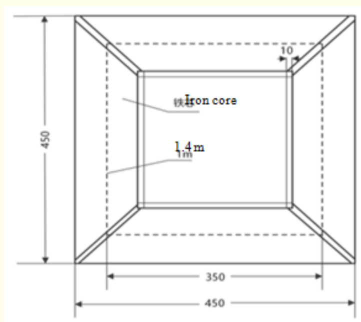

Figure 1: Epstein frame model.

To use the Epstein frame method to measure the magnetic properties of silicon steel sheets, it is an essential and important link to determine the equivalent magnetic circuit length of the frame used. Fig. 1 is a model diagram of the Epstein frame. For the sake of accuracy, the frame magnetic circuit length generally cannot be directly used for its geometric average length, but needs to be measured and determined separately. For example, for the more common standard 25cm Epstein frame, the magnetic circuit length is not 1m, but the equivalent magnetic circuit length (0.94m) specified by the IEC (International Electrotechnical Commission) standard is generally used for measurement. With reference to the national standard, this article derives the calculation equation of the equivalent magnetic circuit length of its core model. According to the definition in the national standard, the calculation of the equivalent magnetic circuit is shown in equation (1):

$$L_e = L_m \frac{m_e}{m} \qquad (1)$$

In equation (1), m_e is the equivalent mass of the model, m is the total mass of the model; L_e is the equivalent magnetic circuit length of the model. Then through the known data parameters in Table 1. Epstein frame parameters, the equivalent magnetic circuit length of the frame can be obtained. Calculated by the above equation, the equivalent mass of the square ring used is 23.8kg, which is equivalent to 1.27m in length.

Technical Parameters	***Silicon steel sheet sample***
Model	30QG120
Density of iron core (kg/m^3)	7.65x10^3
Model core section area (mm^2)	2.87x10^3
Model core quality (kg)	26.3
Number of turns of excitation coil	312
Excitation coil wire density(kg/ m^3)	8.9x10^3
Induction coil turns	312

Table 1: Epstein frame parameters.

Experiment platform

In order to realize the measurement of the hysteresis loop of the grain-oriented silicon steel sheet under PWM excitation, this paper builds the experimental measurement platform shown in Fig. 2 based on the Epstein frame.

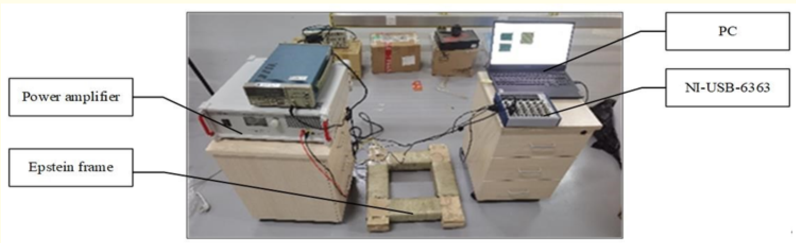

Figure 2: Experiment platform.

The measurement system is mainly composed of the following two parts:

1. Signal generation, data acquisition and processing part. The signal generation and data acquisition and processing are completed by the PC and the data acquisition card (NI-USB-6363). The data acquisition card contains input channels and output channels. The PC can be programmed to output waveforms, and at the same time, use the channels of the data acquisition card to collect B and H signals. This article uses LabVIEW to realize the programming process, and writes the corresponding program in LabVIEW to collect and process the data collected by the data acquisition card.
2. Measuring part. The main part of the measurement consists of the Epstein frame, including the silicon steel sheet under test and the shunt resistor. There are two types of measured voltage signals: the voltage across the shunt resistor on the excitation winding side and the voltage on the induction winding side. The purpose of measuring the voltage across the shunt resistor is to obtain the current through the field winding side. The secondary coil and the primary coil are wound in parallel to enhance the coupling, and the number of turns of the two is equal. The two signals are synchronously collected by the analog input channel of the data acquisition card to strictly ensure the alignment of the signal sequence, and then the data is transmitted to the PC for post-processing.

Principle of the experiment

PWM excitation generation method

The PWM excitation signal required for this measurement is realized by the analog output function of the data acquisition card. The output waveform is amplified by a high-precision power amplifier to the primary side of the Epstein frame as an excitation.

In the traditional silicon steel sheet measurement method, the reference waveform frequency of the magnetic flux density is single, and it is only necessary to control the waveform of the magnetic flux density in the measured sample to be a sine wave according to the reference waveform of the magnetic flux density. Different from the traditional method of measuring the magnetic properties of silicon steel sheets, the PWM power supply contains high-order harmonics, and the order of harmonics can reach several hundred. Under such excitation conditions, to measure the magnetic properties of silicon steel sheets, it is necessary to consider non-sinusoidal magnetic flux density measurement. In order to determine the reference waveform of the magnetic flux density under non-sinusoidal conditions, it is necessary to determine the proportion of each harmonic in the reference waveform. The harmonics in the reference waveform should depend on the PWM power supply [2]. The reference waveform is determined according to equation (2):

$$B(t) = B_1 \sin(2\pi ft) + \sum_{n=2}^{m} k_n B_1 \sin(2\pi nft + \phi_n) \qquad (2)$$

In equation (2), f is the frequency of the fundamental wave, B_1 is the amplitude of the fundamental wave, K_n is the ratio of the amplitude of the n-th harmonic to the amplitude of the fundamental wave, and ϕ_n is the phase of the n-th harmonic.

Experimental measurement principle

In this paper, the Epstein frame method is used to measure the hysteresis loop of the silicon steel sheet. The number of turns of Epstein frame excitation coil (primary side) is N_1, and the number of turns of induction coil (secondary side) is N_2. Connect a shunt resistor in series, the size of the resistor is R. At the same time, according to the law of electromagnetic induction, an exciting magnetic field will be generated in the silicon steel sheet, and the magnetic field strength calculation equation H can be obtained by the law of Ampere's ring:

$$H = \frac{N_1 I}{L} = \frac{N_1 U_1}{RL} \qquad (3)$$

In equation (3), L is the equivalent magnetic circuit length of the Epstein frame, and U_1 is the voltage on both sides of the shunt resistor. According to Faraday's law of electromagnetic induction and the definition of magnetic induction, the magnetic induction B is obtained according to equation (4):

$$B = \frac{\phi}{S} = \frac{1}{N_2 S} \int U_2 dt \qquad (4)$$

In equation (4), S is the cross-sectional area of the coil, and U_2 is the voltage on both sides of the induction coil, which can be collected by the data acquisition card. U_1 and U_2 can be converted into H and B signals after being collected by the data acquisition card, thereby obtaining the hysteresis loop of the sample in the PC.

Result

Measurement of hysteresis loop at different frequencies

In this section, we mainly study the influence of different excitation frequencies on the hysteresis loop of grain-oriented silicon steel sheet. Fig. 3 shows the measurement results of hysteresis loops at 50 Hz, 100 Hz and 200 Hz excitation frequencies when the excitation source amplitudes are equal and the silicon steel sheet is not saturated.

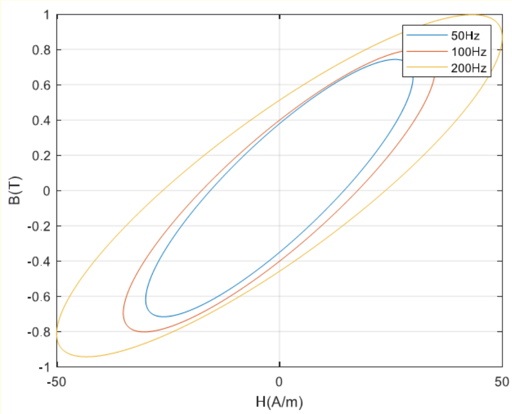

Figure 3: Comparison of calculated and measured hysteresis loops under different exciting frequencies.

As the excitation frequency increases, the area of the hysteresis loop gradually increases, resulting in an increase in loss.

Influence of high order harmonics

This section mainly studies the influence of high harmonics on the measurement results. Fig. 4 is the comparison of the magnetic field intensity under the two excitations. It can be seen that under the PWM excitation, the internal magnetic field intensity of the silicon steel sheet contains a large number of high harmonics.

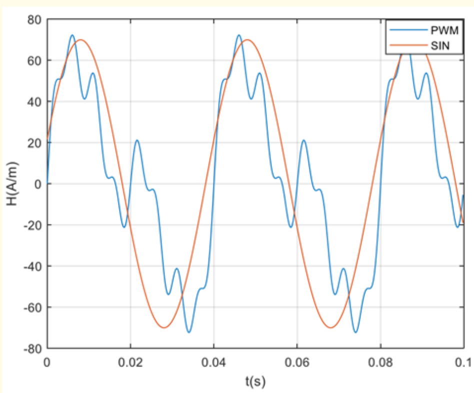

Figure 4: Comparison of magnetic field strength under different excitations.

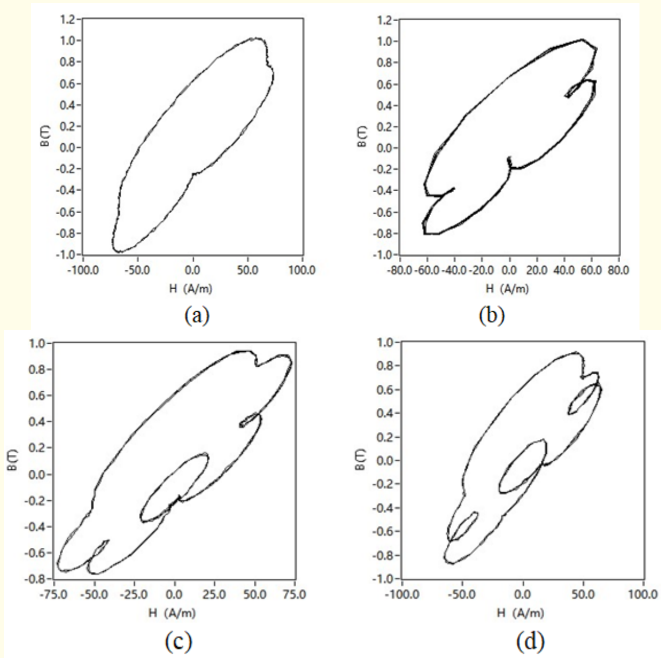

Figure 5: Comparison of calculated and measured hysteresis loops under different exciting frequencies.

Fig. 5 compares the effect of the controlled harmonic order on the hysteresis loop. (PWM excitation, 8 pulses, modulation index 1.2) When the controlled harmonic order is not more than 3, 5, 7, 9, and the hysteresis loop is as shown in the figure. It can be seen that compared with the sine excitation, the measurement result contains a local hysteresis loop. In addition, the increase of high harmonics will affect the shape and size of the local hysteresis loop.

Conclusion

In this paper, based on requirements under PWM excitation, a measurement method suitable for the hysteresis loop of the grain-oriented silicon steel sheet under this condition is adopted. The influence of the frequency characteristics of the hysteresis loop and the high-order harmonics on the magnetic characteristics of the silicon steel sheet is studied.

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