

Measurement of Iron Loss of Silicon Steel in the Highly Saturated State by the Pulsed Magnetic Field Method

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Silicon steel in high-performance electrical equipment usually works at high saturation points (above 2 T) and high frequencies (above 1000 Hz). However, the existing measurement methods based on steady-state excitation are currently difficult to generate sufficient excitation magnetic fields to accurately measure the characteristics of silicon steel under high saturation states and high frequencies. Therefore, this paper proposes the Pulsed Magnetic Field (PMF) method to solve the problem. During the measurement process, a hysteresis loop correction technique is proposed to correct the hysteresis loop. It is found that the excitation magnetic field generated by the pulsed large current can reach above 200,000 A/m and can achieve a high saturation state above 2.3 T. By adjusting the capacitance value, the iron losses within the frequency range of 136 Hz to 1,000 Hz can be measured and the measurement error of iron loss is 3.2%. Depending on the circuit parameters, maximum frequency and induction during measurement can be configured. The PMF method fills the gap in the high-frequency and high saturated state testing area of the existing methods.

Index Terms—Silicon steel, Measurement, Pulsed magnetic field, Iron loss

I. INTRODUCTION

Silicon Steel is widely used in power transformer, high-performance motors, etc. due to their high magnetic permeability and ease of magnetization[1]. High-performance electrical equipment, such as transformers, typically utilize oriented silicon steel sheets and operate at high saturation state, above 2.0T. Motors commonly employ non-oriented silicon steel sheets, characterized by high frequency (above 1000Hz) and high magnetic flux density (above 2.0 T). The increase in magnetic flux density will also lead to a sharp increase in iron losses, which will seriously affect the performance of electrical equipment and even the safe operation of the equipment[3]. Therefore, mastering the working characteristics of materials under unknown working conditions is an issue that scientific researchers should focus on when designing.

The existing measurement methods for silicon steel use alternating current (AC) power supplies [4]. A typical power amplifier, such as the NF4520, has a maximum output voltage of $\pm 200V$, and at high frequencies, it is difficult to achieve a magnetic flux density of 1.8T.

In response to the above issues, this article proposes the pulse magnetic field (PMF) method to measure the iron loss of silicon steel under high saturation. The pulse capacitor releases a huge amount of energy instantaneously to generate a strong excitation current, resulting in a strong excitation magnetic field. According to the discharging characteristics of capacitors, the discharging frequency can be adjusted by changing the capacitance values, so that the iron losses under more frequencies can be measured. Comparison of the test range of the proposed method in this paper with the existing methods is shown in Fig.1.

II. THE PRINCIPLES OF THE PMF METHOD

The comparison between the process of the method proposed in this paper and the circuit of existing methods is shown in Fig. 2.

The PMF method employs a pulsed power supply as the excitation. Firstly, close switch S_1 and open switch S_2 so that the charging module can charge the capacitor bank. Subsequently, open switch S_1 and close switch S_2 to make the capacitor discharge to the excitation winding. The pulse capacitor can

release a huge amount of energy within an extremely short period of time and send a large current into the excitation winding, thereby generating a strong excitation magnetic field and thus meeting the measurement requirements for the high saturation state and high frequency of silicon steel.

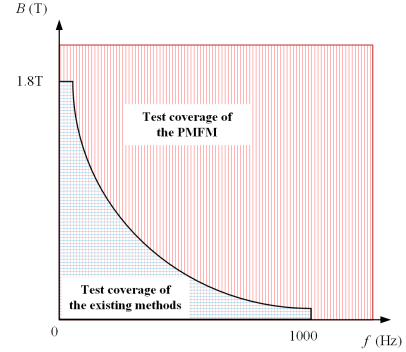


Fig. 1 Comparison of test ranges between the existing methods and the PMF method

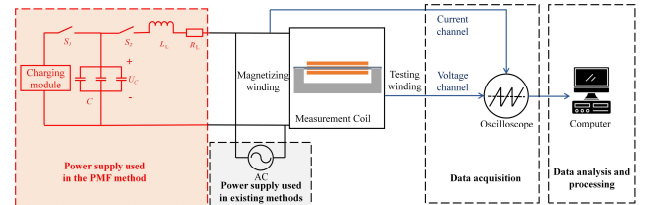


Fig. 2 The principle diagram of the PMF Method

In Fig. 2, L_L and R_L are the line inductance and line resistance, respectively. The coil current i_{Coil} can be found according to the following equation

$$u_C = i_{Coil} R_L + L_L \frac{di_{Coil}}{dt} + u_{Coil} \quad (1)$$

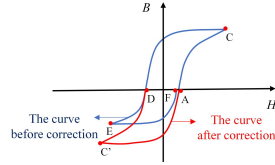
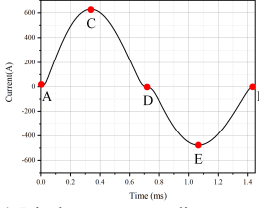
$$i_{Coil} = -C \frac{dU_C}{dt} \quad (2)$$

$$i_{Coil} = \frac{U_0}{\omega L_L} e^{-\frac{R_L}{2L_L}t} \sin(\omega t) \quad (3)$$

$$\omega = \sqrt{\frac{4L_L - R_L^2 C}{4L_L^2 C}} \quad (4)$$

As shown in Fig. 3(a), it is the waveform within a certain cycle when the capacitor is discharging. The characteristic points in the current waveform are marked as Point A to Point

E. It can be seen that the absolute value of the maximum current within a single cycle during the discharging process is greater than that of the minimum current. Therefore, the measured hysteresis loop model is shown by the blue line ACDEF in Fig. 3(b). The third and fourth quadrants are asymmetric and not closed with respect to the first and second quadrants, and the iron loss calculated from this curve is incorrect. Therefore, according to the symmetry of the hysteresis loop, the first and second quadrants of the hysteresis loop are flipped and supplemented to the third and fourth quadrants to complete it as ACDC'A.



(a) Discharge current diagram
Fig. 3 Discharge current and hysteresis loop

The iron loss can be accurately calculated from this loop, and the calculation equation is as follows.

$$P = \frac{f}{\rho_m} \oint_{ACDC'A} H dB \quad (5)$$

In the equation, P represents the iron loss, f represents the frequency, ρ_m represents the mass density, T represents the period, $H(t)$ represents the magnetic field intensity, and $B(t)$ represents the magnetic flux density. The current waveforms at more frequencies can be obtained by adjusting the capacitance, so that the iron losses at multiple frequencies can be acquired.

III. VALIDATION

Calculations were first carried out through simulation to verify the validity of the PMF method. To achieve a larger frequency testing range, it is necessary to reduce the inductance of the testing coil. Commonly used testing methods include the Epstein frame method, single-sheet tester method, and toroidal core tester method. Since the Epstein frame has 700 turns and thus a large inductance, it is not suitable for this method. In this paper, the single-sheet tester is selected for analysis. The simulation model is shown in Fig. 4. The overall design refers to the international standard IEC 60404-16 [5]. The number of coil turns is 200. The sample selected is 35JN270.

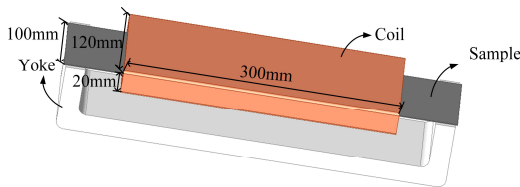


Fig. 4 Simulation model of the single-sheet tester

To verify the correctness of the simulation model, the flux density was first fixed at 1.8T, and the iron losses at frequencies ranging from 100Hz to 900Hz were calculated. The comparison between the simulation results and the experimental results is shown in Fig. 4. The average error is approximately 3.2%.

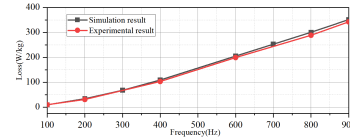


Fig. 5 Comparison between simulation and experiment

Subsequently, the PMF method was simulated, with the capacitance set as 50 μ F, 100 μ F, 250 μ F, 500 μ F, 1000 μ F, 1500 μ F, and 2500 μ F, respectively. The samples were magnetized to 1.9T~2.3 T respectively. The magnetic field strength obtained from the simulation is shown in Fig.6. It can be seen that the PMF method can generate a magnetic field intensity exceeding 200,000 A/m, with a period ranging from 1 ms to 7.3 ms. Therefore, the testable frequency range is from 136 Hz to 1000 Hz. The iron losses of the samples at these frequencies are shown in Fig.7. The experimental results will be given in the full paper.

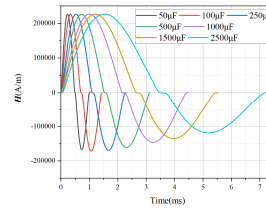


Fig.6 Magnetic field strength under various capacitance values

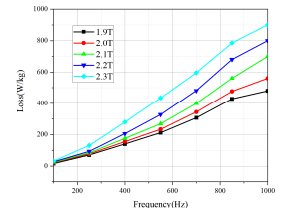


Fig.7 Iron losses at various frequencies

IV. CONCLUSION

This paper proposes a PMF method for measuring the iron loss of silicon steel materials under the conditions of high saturation and high frequency using pulsed magnetic fields. During the measurement process, a hysteresis loop correction technique is proposed to correct the hysteresis loop, and the feasibility of this scheme is verified through simulation. The results show that this method can generate a magnetic field intensity exceeding 200,000 A/m, thus to magnetize the materials to 2.3 T, enabling the measurement of iron loss of silicon steel with excitation from 136 Hz to 1000 Hz, and the measurement error of iron loss is 3.2%. If the number of coil turns is further reduced, the testing frequency can be further increased. Compared with the existing methods, the PMF method greatly expands the testing range of iron loss in silicon steel, and meets the testing requirements of high saturation (above 1.8T) and high frequency (above 1000Hz).

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