Magnetic measurement of nanocrystalline alloy based on a single sheet tester

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Abstract
Generally, for the measurement of magnetic characteristics of nanocrystalline alloy, the magnetic circuit length \( l_m \) is assumed as a constant, and magnetic measurement under square waveform is rarely focused. This paper examines that magnetic characteristics of nanocrystalline alloy are measured under sinusoidal waveforms and square waveforms based on a single sheet tester. The factors related to \( l_m \) are analysed from the tested data under sinusoidal excitations, and a novel method to determine \( l_m \) is presented, which is then extended to the case under square waveforms. By combining with a power electronic inverter, the influence of power electronic topology on measurements is analysed, and the oscillation mechanism of excitation current of single sheet tester is revealed. As a result, the limitation of the H-coil method for acquiring the magnetic field intensity \( H \) under square waveforms is pointed out, and improved magnetic circuit method is introduced. It is shown from experimental results that the proposed measurement system is useful for acquiring magnetisation characteristics of the nanocrystalline alloy.

1 INTRODUCTION

The promotion of the power density in the energy-conversion equipment depends on the improvement of magnetic properties of the core component. Some new materials, typically nanocrystalline alloy, are gradually replacing silicon steel and used as the core of electrical devices, for example, high-frequency transformer. It is significant for the optimisation of electrical devices that the properties of magnetisation and loss of magnetic materials, such as nanocrystalline alloy, are measured and predicted accurately.

The measurement of magnetisation characteristics of magnetic materials has received attention from many scholars for several decades. Toroidal samples benefited from its easily determined magnetic circuit (MC) length, are more often adopted in the experiments. However, the bending process introduced in one toroidal sample inevitably resulted in the inner stress, thus magnetic characteristics acquired from the toroidal sample are different from that of the material itself [1,2]. In order to obtain the materials’ intrinsic characteristics, it is more accurate to carry out measurements on strips. Epstein Frame is widely applied in the magnetic measurement of electrical steel lamination, but not suitable for the measurement of nanocrystalline strips, which is often wound instead of being stacked into the core. Based on single sheet testers, IEC standards for electrical steel (up to 10 kHz) and amorphous strips (up to 400 Hz) under sinusoidal excitations have been revised [3, 4]. It was pointed out that the magnetic voltage drop in the yoke would produce an obvious distinction between the magnetic field intensity acquired from different measurement methods [5]. In order to reduce this distinction, the specific requirement on the dimension of yokes has been given out as standards. In terms of the single sheet tester (SST) for electrical steel, its yokes to make up the MC are required to be 90–150 mm in height, 500 mm ± 5 mm in width, 450 mm ± 1 mm in yokes’ window length. As for the SST for amorphous alloys, the adopted yokes are stipulated as 80 mm- 120 mm in height, 220 mm ± 1 mm in width, 240 mm ± 1 mm in yokes’ window length. However, some scholars have validated that other geometrical dimensions of the SST are also applicable in engineering practice [2, 6–8], especially for nanocrystalline, which is extremely thin in thickness compared with yokes, and its far higher magnetic resistance introduces a much higher magnetic voltage drop in the sample.
In addition to the frame of MC, the signal detection is also significant for the measurement systems of magnetic materials. Remarkably, for low-loss material nanocrystalline alloy, its hysteresis loops are extremely narrow. In order to guarantee the measurement accuracy, methods to obtain the magnetic field intensity and magnetic flux density are supposed to be selected appropriately. Presently, H-coil and MC method is typical in acquiring magnetic field intensity $H$, and related researches have been carried out to explore the source of error in the signal detection of Epstein Frame and SST. For example, Nakata et al. developed a double H-coil method to obtain the field intensity so as to decrease the error introduced by the distance between H-coil and sample, and pointed out this way would invalid at low induction [9]. They also discovered that, for amorphous, the test error would exceed 10% while the length of H-coil beyond the 70% of samples’ length. These conclusions all indicate the H-coil is of high sensitivity. If the measurement system is excited by the voltage waveform of power electronic inverter, which inevitably brings to the overshoot voltage in the excitations, then the test accuracy of H-coil would be affected seriously. However, neither a detailed analysis of oscillation produced mechanism nor the effect of the oscillation on measurement has been illustrated, so that it is difficult to provide an appropriate scheme for acquiring field intensity under this condition. Alternatively, MC method to obtain the magnetic field intensity $H$ originated from the Ampere Law relies on the accurate determination of MC length $l_m$, and some investigations about the influence factor of $l_m$ have been carried out for electrical steel [10–15]. It has been revealed that the MC length is not a constant in the Epstein frame, but varied with magnetic flux density [10]. With this aim, double-Epstein frame has been proposed to deduce the effective MC length [11]. Based on the measurement system, Philip Marketo et al. investigated the variation of $l_m$ under different excitations or that of different materials, and they pointed out that $l_m$ is closely related to both factors [12]. In addition, J. D. Sievert deduced $l_m$ in the SST for FeSi by resolving the relationship between field intensity from H-coil and MC at the same time [13], which is continuously applied in [14]. In addition to the direct way to acquire the variation of $l_m$, some methods to indirectly obtain field intensity have been proposed. For example, a compensation method is introduced to acquire a fixed $l_m$ [15]. Gmyrek designed an SST with variable dimensions. By using the SST, measurements from the same sample twice at the same flux density could lead to the calculation of the magnetic voltage drop effectively, and field intensity could then be acquired [16]. However, the analysis of the variation of $l_m$ in SST is rarely focused, while SST is the most suitable for nanocrystalline alloy’s measurement. As for magnetic flux density, B-needle method and induction coil method are the most common detection techniques. The first method has been applied to nanocrystalline alloy [2, 8], but some scholars pointed out that needles would fall in the material with small grains [17]. The second method is often adopted by electrical steel, and also recommended by the standard for amorphous alloy [4], so this method would be used in this paper.

An SST is built to measure the high-frequency magnetisation and loss characteristics of nanocrystalline strips. Combined with a traditional signal generator and power amplifier, both H-coil method and MC method are applied to the measurement under sinusoidal waveforms, magnetic losses are then obtained and the relationship $l_m(B_0, f)$ is deduced. Next, the SST is connected to power electronic inverter to acquire square waveforms excitation. In this way, not only the limitation of amplifier’s bandwidth is avoided but also the actual application situation in high-frequency electrical devices is established. High-speed power electronic devices used in the system make the parasitic parameters of the testing electric circuit non-negligible, so related oscillation-produced mechanism is illustrated by constructing the equivalent circuit, which provides reference to the selection of suitable measurement method. Furthermore, $l_m(B_0, f)$ is extended to square waveforms by FFT and considering contributions of each harmonic component. While single strip, three-, five-, ten-laminated nanocrystalline strips (multi-strips is glued in this case) are measured in the proposed SST system, deviations among them are analysed, and acquired results validate the reliability of measurement system.

2  |  THE CONSTRUCTION OF SST

The model diagram of SST is shown in Figure 1. Double-U yoke is chosen to provide a closed MC for flowing magnetic flux. However, tested annealed nanocrystalline strip is extremely brittle, so it has to be inserted into the resin frame, which is fixed between limbs of the yoke. Meanwhile, excitation coils wound on the outermost layer of frame and induction coils wound on the second outer layer. This structure is different from the existing literature for nanocrystalline measurement [2, 8], which introduces magnetic yokes wound by excitation coils and B-needles instead of induction coils. Detailed dimensions of the proposed SST are as follows:

1. Double-U yoke manufactured by amorphous alloy has a cross-section of 50 mm × 40 mm, which is far larger than 40 mm × 19.5 μm that of the cross-section of the sample.

2. Induction coils are made of 300 turns of enamel insulated wire, of which the diameter is 0.15 mm. The excitation coils...
TABLE 1 Parameters of the solenoid

| n_1  | n_2 | r_o (mm) | r_i (mm) | L (m) |
|------|-----|----------|----------|-------|
| 922  | 216 | 45.5     | 36.25    | 1.5   |

are made of 100 turns of enamel insulated wire, of which diameter is 0.4 mm. The setting of turns is dependent on the level of detection and signal intensity.

3. Each yoke has a window length of 70 mm, the width of yoke is 50 mm and the height is 105 mm.

4. The tested sample is nanocrystalline alloy 1K107B (Fe_{73.5}Cu_{1}Nb_{3}Si_{15.5}B_{7}). The annealing condition is 550° C, one hour, without a magnetic field. Geometrical size is 130 mm in length and 40 mm in width.

In terms of signal acquisition, Tektronix oscilloscope MDO3054 is used to record the current and voltage waveforms in this measurement system. The bandwidth of oscilloscope is 500 MHz, and sampling rate is 2.5 GS/s. Voltage waveform is detected by probe TPP 1000, of which the bandwidth is 1 GHz, and propagation delay is 5.67 ns. Both MC method and H-coil method are prepared for sinusoidal excitation. For the MC method, the excitation current is acquired by the current probe CT2, of which the bandwidth is 200 MHz and the propagation delay is 6.1 ns.

3 | MEASUREMENT UNDER SINUSOIDAL WAVEFORMS

Measurements of nanocrystalline alloy under sinusoidal waveforms have been carried out by the SST proposed in this paper. A signal generator RIGOL DG1032 (30 MHz) and a power amplifier NF 4502 (20 kHz) are combined with the proposed SST to obtain magnetic characteristics of the tested sample. Remarkably, the H-coil method and MC method are both applied to measurement under sinusoidal waveforms. Then factors influencing \( l_m \) could be deduced.

3.1 | Calibration of the H-coil

As an effective sensor component to acquire the field intensity \( H_s(t) \) from the sample, H-coil is necessary to be calibrated. A 1.5-meters long solenoid is applied to calibrate the H-coil, which can produce a homogeneous magnetic field, and related parameters are given in Table 1, where \( n_1 \) and \( n_2 \) represent the number of turns in a unit length at each layer and the number of layers in a unit thickness respectively, \( r_o \) and \( r_i \) are the outer and inner radius of the solenoid, respectively, while \( L \) is the length of the solenoid.

The solenoid is supposed to work under different frequencies to acquire its coefficient \( N_{1K1} \) precisely. First, the H-coil is fixed at the middle point of the solenoid. By adjusting the excitation current flowing through the solenoid coil, the induction voltage of H-coil \( n_{1K} \) at different frequency is supposed to be recorded. According to the excitation current, flux density located at the place of H-coil can be calculated by (1):

\[
B_{1K} = \frac{1}{2} \mu_0 n_{1K} I \ln \frac{r_o + \sqrt{r_o^2 + \left(\frac{1}{2}\right)^2}}{r_i + \sqrt{r_i^2 + \left(\frac{1}{2}\right)^2}}.
\]

(1)

Combined with detected \( n_{1K} \), assuming that \( K_{1K} = N_{1K} H_{1K} \), it could be resolved by (2), and it is independent of frequency. Next, H-coil would be introduced in the measurement and placed at the middle of the sample to acquire the surface’s field intensity \( H_s(t) \) as (3):

\[
K_{1K} = \frac{1}{B_{1K}} \int n_{1K} dt
\]

(2)

\[
H_s(t) = \frac{1}{\mu_0 K_{1K}} \int n_{1K}(t) dt.
\]

(3)

3.2 | \( l_m \) under sinusoidal waveforms

In the MC of proposed SST, the magnetic voltage drops are composed of three parts, including that in yokes, air gaps, and the sample. The magnetic voltage drops in yokes are negligible since the induction voltage detected on the yokes approximate to zero. So, the MC equation can be expressed as (4)

\[
Ni(t) = H_s(t) \cdot l_s + H_{\delta}(t) \cdot l_{\delta}
\]

(4)

where subscripts \( s \) and \( \delta \) denote the quantities in the sample and air gap, respectively. The magnetic field intensity could be expressed as

\[
H(t) = \frac{\phi(t)}{\mu S}
\]

(5)

where \( \mu \) is permeability, \( S \) represents the relevant cross-section of the sample where the magnetic flux flows through. Remarkably, the magnetic flux is consistent, and the magnetic field intensity satisfied \( H_{\delta}(t) \gg H_s(t) \). Assuming that

\[
H_{\delta}(t) = H_s(t) + \Delta H(t)
\]

(6)

and substituting (6) into (4), we can obtain

\[
Ni(t) = H_s(t) (l_s + l_{\delta}) + \Delta H(t) l_{\delta} = H_s(t) l_m + \Delta H(t) l_{\delta}.
\]

(7)

Based on the above analysis, the relationship between \( i(t) \) and \( H_s(t) \) is supposed to be investigated.

Refer to Section 3.1, \( H_s(t) \) could be detected easily, at the same time, the number of turns in the excitation coils and current flowing through it are also known. According to the experimental results, the dependence of \( Ni(t) \) on \( H_s(t) \) is linear as shown in Figure 2, and this indicates that the change of \( \Delta H(t) l_{\delta} \) is even...
negligible at different excitation levels. In such a case, \( l_m \) is equal to the slope of this function. Then, the relationship of \( l_m(B_p, f) \) is analysed under sinusoidal waveforms.

The variation of \( l_m \) along with frequencies is depicted in Figure 3. Obviously, at the same level of flux density, \( l_m \) mostly remains stable at different frequencies, at least for the range of frequencies this paper investigates. In terms of flux density, as shown in Figure 4, the relationship between \( l_m \) and \( B_p \) could be fitted as (8)

\[
l_m = 0.06147 - 0.02431B_p + 0.01265B_p^2,
\]

which is obtained from results at \( f = 10 \text{ kHz} \), and has been validated at different frequencies. Remarkably, it is more accurate to set equivalent MC length as a constant as \( B \) exceeding 1 T, which indicates a saturated state. Based on the analysis above, Equation (8) is applied to calculate points in Figure 3, and results show that deviations are less than 5%, so this conclusion is convincing.

Additionally, multi-laminated strips are introduced in this part. \( l_m \) also varied with different laminated strips. It is obviously known from experimental results that no matter how many strips laminated are under test, the variation of \( l_m \) along with flux density still satisfied a second-order polynomial, as depicted in Figure 5a. However, this conclusion could only be used in a limited range of frequencies, once frequency getting higher into 20 kHz, as shown in Figure 5b that \( l_m \) getting relatively stable, and shorter than that of lower frequency. And at 10 kHz, the increase in the number of laminated strips actually leads to a longer \( l_m \), which is underestimated by (8).

As a matter of fact, \( l_m \) is related to permeability \( \mu \), which decreases with the increasing magnetic flux density in the investigated range, and also declines while frequency reaches into a certain value [18]. Besides, different \( l_m \) existing in the laminations is attributed to the variation of \( \mu \). The sample’s cross-section would be increased with the number of laminations, so \( \mu \) is increased and brings to a higher \( l_m \).

3.3 Magnetic losses under both methods

Based on the H-coil and MC method, hysteresis loops of the sample are measured, and relevant results are shown in Figure 6. Additionally, in order to validate the accuracy of deduction, the other yoke with different dimensions is also introduced to examine the proposed method. Meanwhile, the H-coil method and MC method are both applied in this section to make a comparison. Results of magnetic losses from these two methods in every yokes group are approximate, and results at \( f = 10 \text{ kHz} \) are depicted in Figure 7.

4 MEASUREMENT UNDER SQUARE WAVEFORMS

Instead of a signal generator and power amplifier, a full bridge inverter circuit is used to provide square waveform excitations, in which silicon carbide (SiC) MOSFET is chosen to satisfy
the high-frequency measured requirement. The structure of the measurement system is depicted in Figure 8. $C_1$ often is used to isolate alternating disturbance signal from output of dc source. Remarkably, $C_1$ could also effectively prevent the voltage overshoot generated from power electronic circuit. According to [19], this capacitance could be calculated with the prior knowledge of the maximum appeared in the overshoot of current and voltage. The low-inductance capacitance $C_1$ connecting in parallel to the dc-bus could reduce the total inductance in the inverter circuit. In this way, the excitation waveform could be idealised to some extent. With the inverter supply, on the one hand, the measured bandwidth would not
be limited by the amplifier. On the other hand, this working condition is consistent with the actual application of magnetic materials, such as dc–dc converter. A digital signal processor (DSP) is used to control the turn ON/OFF of SiC MOSFET and convert the dc voltage into the alternating voltage at the frequency required. However, overshoot in the excitations is sensitive to the parasitic parameters of the excitation coil loop, so it is necessary to analyse the influence of parasitic parameters on the measurement and obtain reliable results.

4.1 Equivalent circuit of the SST

The wideband equivalent circuit for SST is constructed in this part to take the effect of parasitic capacitance at the excitation side into account. A suitable measurement method for the system is to be determined. The layout of coils and sample in the proposed system are shown in Figure 9b. Excitation coils and induction coils both wound on the frame supporting the tested sample. Unlike the system with excitation coils wound on the yoke [20, 21], where induction voltage is acquired by the B-needle technique or induction coils far from excitation coils, the proposed system introduces a higher capacitance to ground according to (10):

\[ C = \frac{\varepsilon s}{d}. \]  

It is a common expression for parallel plate capacitance, \( s \) is the cross-section, \( d \) is the distance between two plates. Compared to Figure 9a, the frame fixed between coils and samples also leads to a higher dielectric constant \( \varepsilon \). Besides, in this paper, relatively narrow pole-distance of yokes and large-number turns of coils lead to the increase of coils’ layers, which result in the increase of interlayer capacitance \( C_{\text{layer}} \). So, current oscillation is more seriously contributed from voltage overshoot due to the differential relationship between the voltage and current:

\[ i = C \frac{dV}{dt}. \]  

Experiments have been carried out at \( f = 5 \) kHz under square waveform, and the oscillation period of induction voltage under different laminated strips are shown in Table 2. Obviously, after laminations inserted, the capacitance introduced by coils and core are contributed from the conductor in the coil and tested sample, they also belong to \( C_{\text{ground}} \). More laminations lead to a shorter \( d \), so the higher \( C_{\text{ground}} \) would be obtained. The oscillation frequency can be calculated by

\[ f_{\text{osc}} = \frac{1}{2\pi \sqrt{LC}}. \]  

where \( L \) and \( C \) are the total inductance and capacitance in the excitation coil loop, respectively. These phenomena could further validate the above-mentioned analysis on system’s capacitance, and reflect the effect of capacitance on the SST for the nanocrystalline alloy.

Taking \( C_{\text{layer}} \) and \( C_{\text{ground}} \) into account, the partial capacitance network of the excitation coil is shown in Figure 10a, and the capacitances could be converted as terminal capacitances in Figure 10b. Thus, the equivalent circuit of the SST is shown in Figure 10c. Obviously, a dramatic oscillation in current is produced while the excitation voltage appearing slightly overshot. More seriously, the oscillation in the induction coil’s voltage would maintain the same time with the excitation coil, while the \( f_{\text{osc}} \) is higher in the latter one, as shown in Figure 11. In terms of the oscillation in the H-coil, it keeps longer time and leads to a total distortion of H-coil voltage, which means the H-coil

| Numbers | Oscillation period for different laminated strips |
|---------|-----------------------------------------------|
| Period (μs) | 0 | 1 | 3 | 5 | 10 |
| 0 | 1.72–1.8 | 1.96–2.2 | 2.09–2.22 | 2.18–2.26 | 2.24–2.28 |

**TABLE 2**

**FIGURE 7** The comparison of magnetic losses at \( f = 10 \) kHz

**FIGURE 8** The structure of measurement system with a full bridge inverter

**FIGURE 9** The layout of coils and sample. (a) Without frame and (b) with frame. 1. nanocrystalline strip; 2. induction coils; 3. excitation coils; 4. resin frame

**FIGURE 10**

**FIGURE 11**

The structure of measurement system with a full bridge inverter
Figure 10 The wideband equivalent circuit. (a) Partial capacitance network of the excitation coil. (b) Terminal capacitance network of the excitation coil. (c) Equivalent two-port network model for SST

Figure 11 The oscillation phenomenon in the excitation coils and induction coils

Method is not suitable for field intensity detection in this case. Therefore, the MC method is adopted by the measurement under square waveforms, and at the next step, it is significant to acquire \( l_m \) in this excitation.

4.2 \( l_m \) under square waveforms

According to Fourier Transformation, any waveform could be represented by a superposition of sinusoidal waveforms with different frequencies and amplitudes. Sinusoidal waveforms avoid the influence of switch-ON and OFF process in the power electronic device, and \( l_m \) in this case has been identified in Section 3.2. Meanwhile, relevant variation law could then be extended to the non-sinusoidal cases. The square waveform actually could be represented as (13)

\[
\sum_{n=1}^{\infty} U_1^n \sin(n\omega t)
\]

where \( U_1^n \) represents the amplitude of \( n \)-order harmonic of square waveform and satisfies (14):

\[
U_1^n = \frac{U_p}{\pi n} \left[ 1 - \cos(n\pi) \right] \sin\left(\frac{\pi n}{2}\right)
\]

where \( U_p \) is the peak value of the square waveform. Therefore, the amplitude of harmonic could be acquired, and four kinds of harmonic in Table 3 cannot be ignored due to their significance.

According to the analysis in Section 3.2, \( l_m(B_p) \) satisfied formula (8) in the investigated frequency range. As the frequency increases to a certain level, the permeability will drop dramatically and \( l_m \) is supposed to be regarded as a constant, which is equal to the value of the saturated situation. The skin effect appears at about 20–30 kHz for the strip of nanocrystalline alloy referring to the brochure from the manufacturer, and the frequency would be distinct in different materials and relevant annealing condition. Therefore, based on the measurement under square waveform at \( f = 5 \) kHz carried out in this paper, formula (8) is still applicable in the first-, third-, and fifth-order harmonic. In terms of the seventh-order harmonic, relevant MC length could be obtained from (8) by assuming \( B_p = B_{0w} \), which is the saturated flux density for the material. Then, considering contributions from \( l_m \) in each harmonic component, MC length under square waveforms \( l_{m,squ} \) could be expressed as formula (16):

\[
l_{m,squ}(B_p) = k_1 l_1(B_p) + k_3 l_3(B_p) + k_5 l_5(B_p) + k_7 l_7(B_{0w})
\]

\[
k_n = \frac{U_1^n}{\sum_{n=1}^{7} U_1^n} \quad (n = 1, 3, 5, 7, ...)
\]

formula (8) could be deduced into the case under square waveforms, as expressed in formula (18):

\[
l_{m,squ}(B_p) = 0.06147 - 0.02431 \cdot (0.92 \cdot B_p) + 0.01265 \cdot 0.92(B_p)^2
\]

4.3 Magnetic losses under square waveform

Measurements have been carried out under square waveforms based on test bench shown in Figure 12. During the measurement, current in excitation coils and voltage in induction coils

Table 3 Harmonic content in the square waveform

| Order | First   | Third  | Fifth  | Seventh |
|-------|---------|--------|--------|---------|
| Amplitude | \( U_p \) | \( 0.424U_p \) | \( 0.255U_p \) | \( 0.182U_p \) |

\[
u(t) = \sum_{n=1}^{\infty} U_1^n \sin(n\omega t)
\]
are detected by probes, and then recorded in the oscilloscope. The full-bridge inverter, which offers the excitation signal for the SST, is responsible for converting the dc voltage from the dc source into the alternating signal under the control of the DSP, while the auxiliary supply module is used to supply for the driving module in the inverter. Geometrical parameters of samples are known, once \( l_m \) is obtained from the proposed method, combined with Ampere’s Law and Faraday’s Law respectively, \( H \) and \( B \) are acquired, thus hysteresis loops are produced. Remarkably, single-, three-, five-, ten-laminated strips are tested in this work, in addition to the mentioned parasitic capacitance analysis, the accuracy of measurement system could also be validated in this way.

Magnetic losses produced by these four kinds of samples are investigated in this part. Based on the \( l_m \) obtained from a single sheet, Ampere’s Law is applied to calculate the field intensity in all cases. Hysteresis loops of single strip at \( f = 5 \text{ kHz} \) are depicted in Figure 13, they are not smooth as results from H-coil method, since the latter one contains an integral process to avoid burr. Besides, the thickness of nanocrystalline is much smaller than electrical steel, thus acquired signal is so weak that being easily influenced by surrounding noise. The curve \( P(B) \) measured from different samples is shown in Figure 14. Every sample has been measured repetitively, and it is obvious that both measurements are consistent approximately. However, at the same level of frequency and flux density, higher losses appear in the multi-laminated strips, and this phenomenon could be explained as the variation of \( l_m \). As illustrated in Section 3.2, Equation (18) leads to the underestimation in multi-laminated samples’ \( l_m \), so field intensity is overestimated.

In addition, it needs to be mentioned that inverter supply controlling output voltage relies on dc source, which is limited by the accuracy of the apparatus itself. Therefore, it is difficult to carry out measurements at presumed flux density, which is adjusted by a knob in the control panel. However, this factor does not affect the results of the curve \( P(B) \). The accuracy of this system could be verified by repetitive measurements and deviation analysis mentioned above.

5 | CONCLUSION

An SST for the nanocrystalline alloy is constructed in this paper. Both the H-coil method and MC method are applied to tests under sinusoidal waveforms, and \( l_m(B_p,f) \) is deduced instead of assuming \( l_m \) is a constant. Comparison between magnetic losses from different methods validates the accuracy of the system. Furthermore, combined with power electronic inverter, magnetic characteristics under square waveform are investigated. The effect of circuit topology on the measurement system is first evaluated, and an appropriate scheme for field intensity acquisition is determined. Some conclusions are summarised as follows:
1. A snubber capacitance is necessary to overcome the voltage overshoot in the excitation coils, and it could be identified by the inductance of power circuit in PCB, overshoot voltage, and current without capacitance. Even though, some oscillation in the primary current is inevitable and is attributed to the parasitic capacitance between different turns or layers. Combined with the location of coils, the oscillation under the different number of laminated strips is analysed to reveal the difficulty in the single sheet measurement. And the low signal-noise ratio of the H-coil made itself no longer suitable for this measurement.

2. \( L_m \) is decreasing with the flux density until materials reaching saturation and remain stable with frequency for nanocrystalline alloy without the skin effect. This variation of \( L_m \) resulted from \( \mu \), which would also be influenced by the cross-section of multi-laminated strips. Based on acquired \( L_m(B_p/f) \) under sinusoidal waveforms, \( L_m \) under square waveform is deduced by FFT, then field intensity could be accurately calculated by the MC method.

3. From \( P(B) \) curve under square waveform, the loss of multi-laminations is obviously higher than that of a single strip. This case is reasonable and might be associated with the under-estimation of \( L_m \) by fitting formula from a single strip. On the other hand, repetitive measurement results shown in Figure 14 validate that the measurement system is reliable.

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