

Core Losses Analysis for Soft Magnetic Materials under SPWM Excitations

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Abstract This paper illustrates the core loss analysis for non-grain-oriented silicon steel, grain-oriented silicon steel, and soft magnetic composite (SMC) materials under sinusoidal excitation and Sinusoidal Pulse Width Modulated (SPWM) excitations. The SPWM voltages with their modulation and carrier ratio have been created by MATLAB for experimental verification. The standardized measurement methods: Epstein Frame method and ring sample method, have been used to test the soft magnetic materials. The core losses from different experimental data have been analyzed. The results show that the core losses under three different SPWM excitations depending on the modulation and carrier ratios of PWM waveforms are different from the core losses supplied by sinusoidal excitations. And also, it can be found that the magnetic behavior of the material affects the core loss under non-sinusoidal excitation.

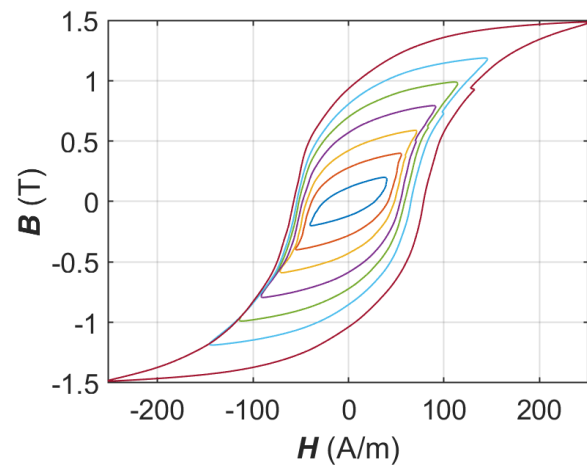
Keywords Core losses, Non grain-oriented silicon steel, Grain-oriented silicon steel, SMC material, SPWM

1. Introduction

Modern AC motors and electromechanical drives are fed through voltage source inverters (VSI) using sinusoidal pulse width modulation (SPWM) schemes [1]. Particularly, it can be considered as the standard solution when voltage and frequency regulation is required, for control and energy savings [2]. Generally, there are two major losses in electrical drives: copper losses, and core losses. The copper losses are relatively easy to calculate from machine windings. However, the calculation of core losses is much more complex under non-sinusoidal excitation because of the non-linearity of induction waveform and materials behaviour. Many kinds of research have been done for core loss estimation under sinusoidal excitation including empirical method, Steinmetz equation [3]. Unfortunately, there are no international standards for core loss measurement under non-sinusoidal excitation. Expanding the use of the SPWM scheme, the core loss measurement has also become an essential role in electrical drives [2]. The author discussed [4], loss analysis of soft magnetic ring core under SPWM and space vector pulse width modulation (SPVM) by using the ring sample method. However, the flux density waveform and hysteresis loop have not been shown. The unsymmetrical hysteresis loop due to the DC

bias condition with PWM excitations has been discussed and introduced to the isolation transformer in the measurement circuit [5]. However, the material behaviour under SPWM with the low modulation and carrier ratios (i.e. $M < 0.5$ and $N < 0.5$) has not been discussed yet.

Therefore, the experimental verification of magnetic materials, i.e. non grain-oriented silicon steel (B35A230), cold-rolled grain-oriented silicon steel (30Q120) and Soft Magnetic Composite SMC, has been analysed under SPWM excitations in this paper. The hysteresis loop has also been presented here. Eventually, the core losses under the three different SPWM excitations, with low, middle and high ratios, and sine voltage have been compared for three testing materials. Figure 1 shows the hysteresis loop for three materials under sinusoidal excitation.



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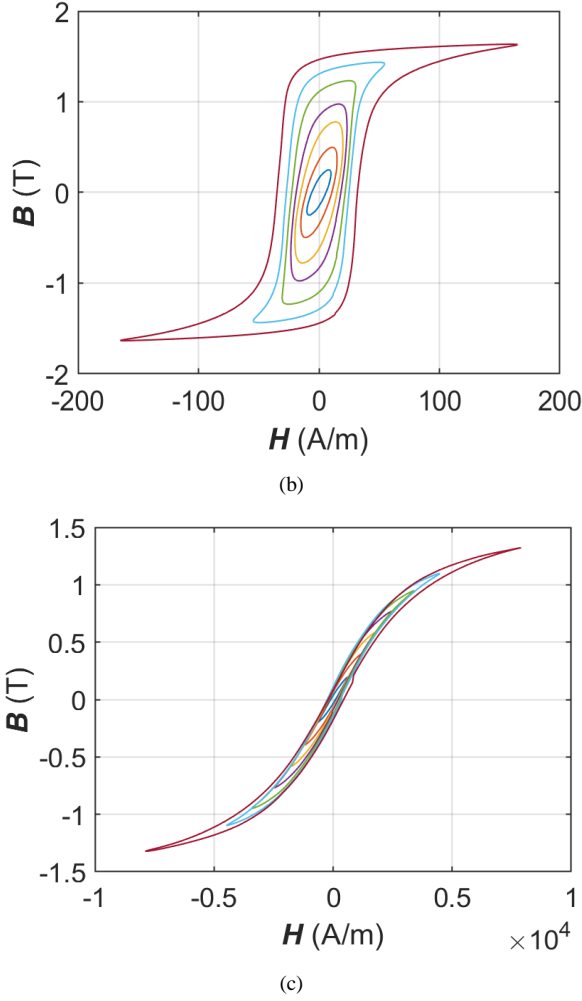


Figure 1. Hysteresis loop for each soft magnetic material under Sine (50Hz): (a) NO steel (b) GO steel (c) SMC

2. Sinusoidal Pulse Width Modulation (SPWM)

The SPWM waveform can be generated by comparing one or two sinusoidal reference signals with a triangular carrier wave, and the width of each pulse varied proportionally to the amplitude of a sine wave evaluated at the centre of the same pulse. There are two types of SPWM which are three-level (unipolar) and two-level (bipolar) switching. Two-level SPWM is not widely used because of requiring large filters at the output due to the high harmonics content and the switching losses are more [6]. This measurement takes the three-level SPWM as a sample to signify multi-level SPWM for evaluation. The modulation ratio (M) and carrier wave ratio (N) of SPWM can be defined as:

$$M = \frac{U_r}{U_c} \quad (1a)$$

$$N = \frac{f_c}{f_r} \quad (1b)$$

Where U_r is the amplitude of modulation wave, U_c is the amplitude of carrier wave, f_r is modulation wave frequency, and f_c is carrier wave frequency. For the measurement, three different ratios of three-level SPWM were chosen, and the base frequency is 50Hz and the base amplitude is 1V for sine wave. The three-level SPWM waveforms are generated with the different modulation ratios and carrier wave ratios: low ratio ($M=0.2$ and $N=20$), middle ratio ($M=0.5$ and $N=50$) and high ratio ($M=0.8$ and $N=80$) by using MATLAB Simulink. Three-level SPWM waveforms are illustrated in Figure 2.

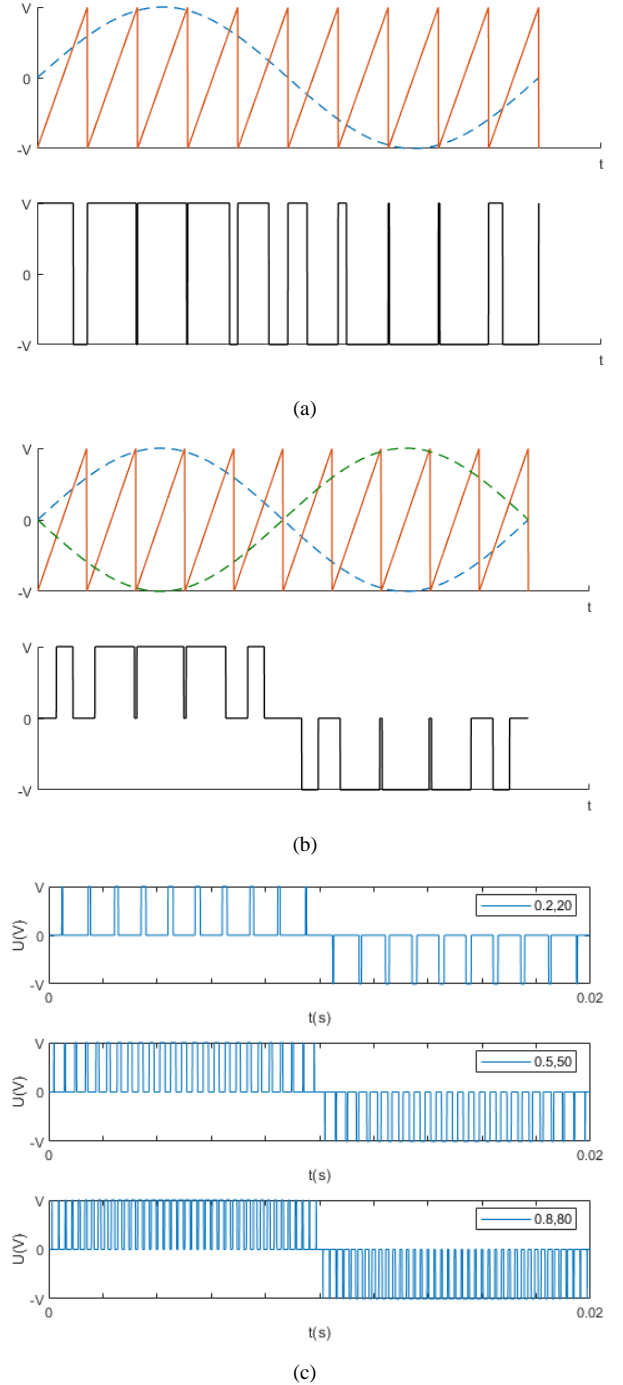


Figure 2. (a) Two-level SPWM, (b) Three-level SPWM and (c) Three-level SPWM waveforms with low, middle and high ratios by MATLAB Simulink

3. Measurement Setup and Principle

3.1. Measurement Scheme

Figure 3 illustrates the measurement scheme of this paper. According to the International Standard IEC 60404-2 [7], the measurement circuit consists of a 25cm Epstein frame or ring core sample with the primary and secondary windings. In the Epstein frame unit, each winding is 700 turns uniformly wound. The specimen of 30mm width, 300mm length testing steel sheets have been inserted into the Epstein frame and five sheets for each side. For SMC materials, the primary winding is 316 turns and the secondary winding is 50 turns. The existence of DC components can be reduced in the PWM voltage source by adding a two-ohm resistor in the excitation circuit [5].

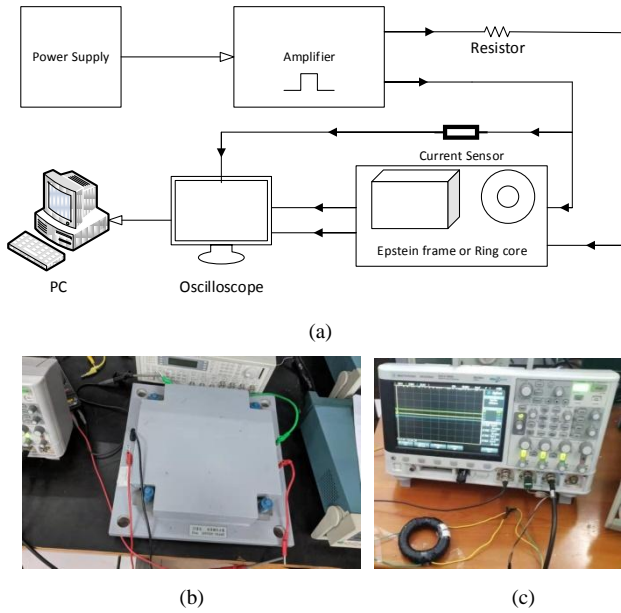


Figure 3. (a) Scheme of measurement (b) Epstein frame measurement (c) Ring core measurement

The effective magnetic path length for the 25cm Epstein frame was set to 940mm [7] and the magnetics' characteristics of the testing materials are shown in table 1.

Table 1. The magnetics' characteristics of the testing materials

Name	NO steel (B35A230)	GO steel (30Q120)	SMC
Thickness (mm)	0.35	0.3	-
Density (kg/dm ³)	7.6	7.65	7.4
Magnetic path length l_m (mm)	940	940	227
Effective area A_e (mm ²)	52.5	42.14	72.75
Height h (mm)	-	-	9.7
Outer diameter D (mm)	-	-	80
Inner diameter d (mm)	-	-	65

3.2. Measurement Principle

These SPWM voltages have been created in MATLAB Simulink and changed to the (.tfw) file which can be uploaded to the amplifier by using the manufacture's amplifier software, Arbexpress. The oscilloscope collected the information of primary voltage from the amplifier, the secondary voltage from secondary winding and the current from the current sensor. According to this information, magnetizing force $H(t)$ in the specimen is:

$$H(t) = \frac{N_p i_p(t)}{l_m} \quad (2)$$

Where N_p is the number of turns in the primary winding, i_p is the current flowing in the primary winding and l_m is the mean magnetic path length of the core. The secondary winding is used to measure the magnetic flux density B created by the primary winding current. Average flux density B can be calculated by using:

$$B = \frac{1}{N_s A_e} \int v_s dt \quad (3)$$

After that, the B - H loops are plotted. Based on the core losses separation model [8], the specific core losses P (in [W/kg]) can be determined by this equation:

$$P = \frac{f}{\rho_{fe}} \oint_{loop} H dB \quad (4)$$

Where f is the frequency of excitation voltage, and ρ_{fe} is the specific mass density of the testing magnetic materials [9]. All these calculation processes can be done in the MATLAB program.

3.3. Core Losses Equation

Traditionally, the Steinmetz equation (SE) method [3], the empirical equation, is mainly adopted to calculate core losses for sinusoidal excitations. Manufacturers also present the core losses in the form of SE such as:

$$P = k \cdot f^\alpha \cdot B_m^\beta \quad (5)$$

Where B_m is the peak flux amplitude, α is the frequency-dependent and β is the flux density-dependent. These two variables can be obtained by using a curve fitting method with the specific frequency range. Figure 4 shows each core loss under 50Hz frequency Sine waves and table 2 shows the fitting values of α and β for all testing materials. This data has been used to verify the actual measurement results in the next section.

Table 2. Fitting parameters at Sine 50Hz

Name	k	α	β
NO steel (B35A230)	0.7124	0.1441	1.664
GO steel (30Q120)	0.1051	0.3195	2.917
SMC	1.587	0.3696	1.995

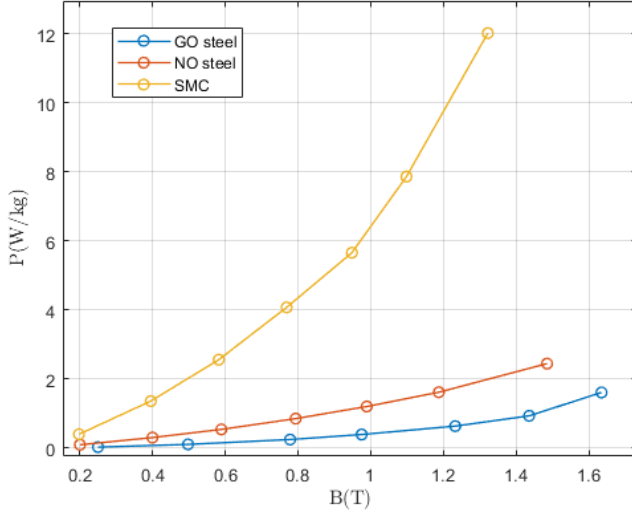


Figure 4. Core loss for three testing materials at Sine 50Hz

4. Testing Results and Discussion

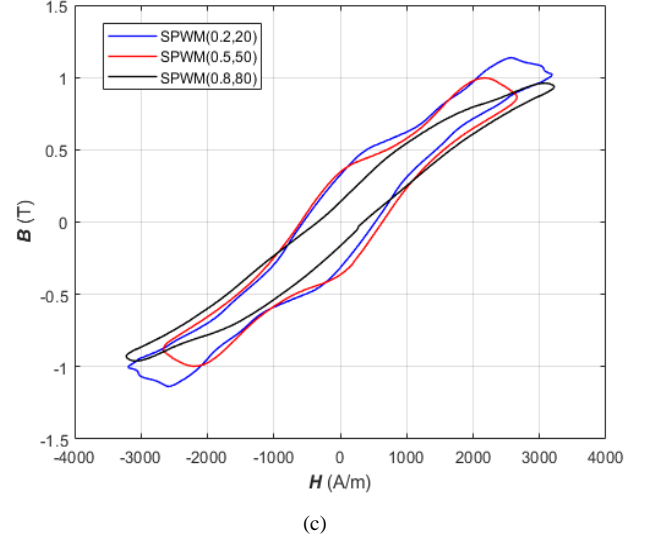
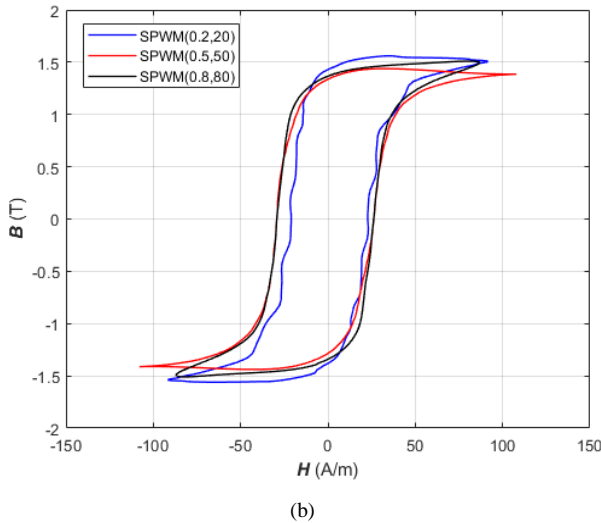
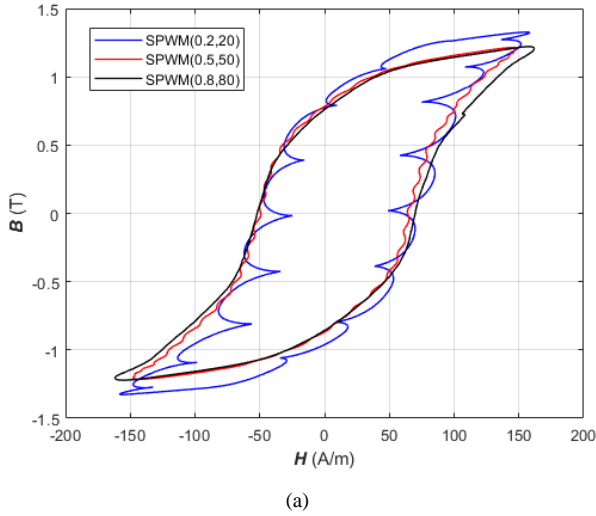


Figure 5. Hysteresis loop for testing materials under SPWM excitations: (a) NO steel (b) GO steel (c) SMC

Here, the result of the measurement system under SPWM is examined. In SPWM ($M=0.2$ and $N=20$), the shape of the hysteresis loop is quite different from ($M=0.5$ and $N=50$) and ($M=0.8$ and $N=80$), it also happens in B waveform because of the higher harmonic contents in the ($M=0.2$ and $N=20$). Figure 5.b shows the results of grain-oriented silicon steel. By comparing it with Figure 5.a, the GO steel's hysteresis loop is more stable and the flux density B waveform is the same as in Sine excitation. The grains size of NO steel is smaller than the GO steel and the manufacturing process is to obtain the random orientation of grains in order to create fully isotropic material [10]. Due to the anisotropy of GO steels, the magnetic flux can easily get a stationary state without the rotation of grains. Such material is widely used in the transformer's core. In figure 5.c, the hysteresis loop is not a regular shape however, the symmetric hysteresis loop shows that can neglect the DC bias magnetization. If the presence of DC bias is in excitation, it will be corrupted the asymmetric hysteresis loop in this measurement. When the excitation flux is over 1T, the current in primary winding becomes excesses because there are high harmonics content in the SPWM excitation. According to equation (4), the core losses of the three testing materials can be calculated. For the sake of completeness and for comparison, the manufacturer's core losses equation under sine excitation is shown in this research work.

Figure 6 shows each specific core losses P for NO steel, and GO steel by using Epstein frame measurement, and the SMC materials using ring core sample under Sine and SPWM excitations. The measurement results show that the experimental data under Sine excitation are quite similar to the manufacturer data. However, the core losses equation (5) is only valid for the Sinewave [3].

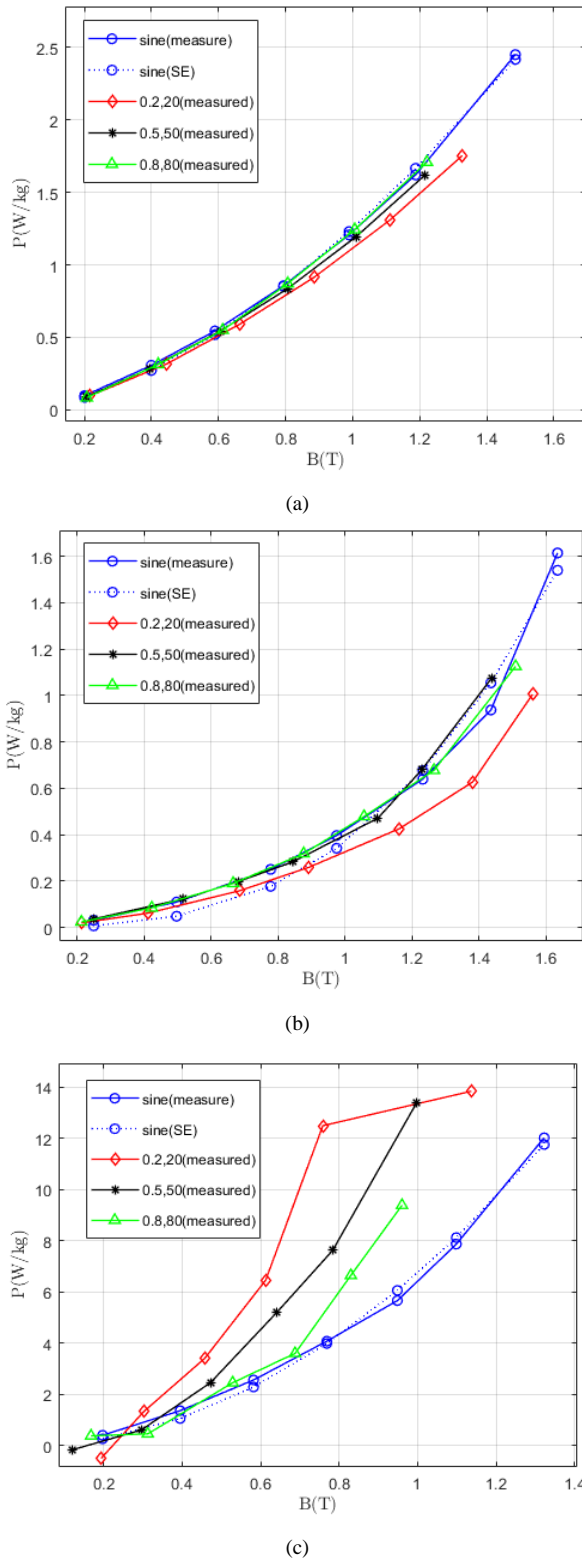


Figure 6. Each specific core loss P under both Sine and SPWM voltage excitations (a) NO steel, (b) GO steel and (c) SMC

In NO and GO steels, the core loss under Sine and SPWM are close to each other. On the other hand, the core loss for SMC material with SPWM excitation is more different from Sine excitation and non-linear behavior has shown in a low ratio of SPWM ($M=0.2$ and $N=20$) because there are more

harmonics contents in SPWM with low ratio than the middle and high ratios. The higher ratio of SPWM has a similarity with the Sine wave and core losses are slightly equal. Comparing these two steel measurements, the core loss of NO steel is much higher than the GO steel. Because the non-grain-oriented steel has isotropic properties and cost considerations, it is useful especially in the motor but the grain-oriented steel has anisotropic properties, costly, low core losses and high magnetic permeability [11]. That kind of steel is used especially in transformers in transformers. In fact, the core loss difference of grain-oriented and non-grain-oriented steels cannot be easily assessed. It can be found that there are many factors such as thickness, permeability, and domain size of the material that influenced the core loss difference. The soft magnetic composite (SMC) material is made by the iron particle and it is insulated by coating. It has low eddy current loss, high saturation flux and low-cost mass production due to the powder metallurgy method which is a cost-effective method for producing a high volume of consistent parts [12]. Generally, silicon steel has a better performance than the SMC at low frequency. On the other hand, the soft magnetic composite material has lower losses than the electrical steels at high frequency. The main advantage of SMC is that it can get complex shapes for various designs. Choosing the right material for a specific design is the essential work for the design engineers.

5. Conclusions

In this work, the core loss for non-grain-oriented steel, grain-oriented steel and soft magnetic composite material with sine and sinusoidal pulse width modulated excitations have been discussed. The hysteresis loop of three materials under SPWM excitations have also been presented. According to the experimental data, silicon steel has good performance at low frequency, especially in grain-oriented steel. However, the excitation frequency 50Hz is the low-frequency range for SMC material and it cannot get better performance than the silicon steel. Isotropic and anisotropic properties of the magnetic material are also an important role for machine designers. Low modulation and carrier ratio of SPWM can cause more core loss because of higher harmonics content. It is sure that the core loss measurement under the PWM scheme plays an important role in the electrical industry.

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