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# Comparative Core Loss Calculation Methods for Magnetic Materials under Harmonics Effect

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**Abstract.** The general data of industrial electromagnetics materials are given only for sinusoidal waveform, and mostly load is non-linear which may cause the harmonics effect. Steinmetz parameters, the well-known empirical equation, also differ under different frequencies and only for sinusoidal. Generalized Steinmetz equation and improved generalized Steinmetz equation are used to predicting the core loss under non-sinusoidal excitation. In this paper, a brief introduction of core loss calculation methods under non-sinusoidal excitations is discussed, and comparative analysis of under different harmonics orders and contents are presented. Ferrite N87 and Nano-crystalline 1K107 ring samples are magnetized as for experimental results. The experimental results show that the core loss depends not only frequency but also on the harmonics effect.

## 1.Introduction

For the computer-aided design of magnetic power devices, including electric machines, transformers, inductors, and other static reactors, an accurate prediction of loss in magnetic materials is essential for machine designer and operator. Traditionally, hysteresis models, core loss separation method and Steinmetz equation (SE) method, are mainly adopted to calculate core loss for sinusoidal excitations. A widely used empirical equation is Steinmetz equation (SE) [1], [2].

$$P = k \cdot B_m^\beta \cdot f^\alpha \quad (1)$$

Where  $B_m$  is the peak flux amplitude,  $P$  is the time-average power loss per unit volume of material,  $f$  is the excitation frequency  $k$ ,  $\alpha$ , and  $\beta$  are Steinmetz's constants, can be calculated by curve fitting. Charles Proteus Steinmetz proposed original equation but without the frequency dependence in 1892. It only works for sinusoidal waveform [3], and one set of parameters only works for a limited frequency range. Due to the developing of technology, a widely used of power electronics devices and most of the electric machine is not sinusoidal excitations. However, it also introduces a massive non-linear load, which brings different harmonics effect. These non-sinusoidal waveforms result in different losses [4], [5]. Nowadays using converters in electric machine control and power electronics field is much developing and it introduces the necessity to study core losses of magnetic materials under non-sinusoidal excitation conditions [6]. As the results, the modified SE (MSE) [7], the generalized SE (GSE) [8] and the improved generalized SE (IGSE) [9] have been developed which use the SE parameters, but extend the calculation to address arbitrary waveforms. On the other way,



we used the standardized measurement method to calculate core loss from the experimental results, i.e., Epstein Frame method [10].

## 2. Review of Existing Methods

### 2.1. MSE

A first approach to calculate core losses caused by non-sinusoidal waveforms is the so-called modified Steinmetz equation (MSE), is based on real motivation that domain wall motion loss depends on  $dB/dt$ . It relates the time variation of magnetic flux density ( $dB/dt$ ) to the core loss and uses the equivalent frequency  $f_{eq}$  in SE (1). The MSE is given as follows:

$$P_{MSE} = (k \cdot f_{eq}^{\alpha-1} \cdot B_m^\beta) \cdot f \quad (2)$$

$$f_{eq} = \frac{2}{\Delta B^2 \pi^2} \int_0^T \left( \frac{dB}{dt} \right)^2 dt \quad (3)$$

Where  $B_m$  is the maximum magnetic flux density,  $\Delta B$  is the peak-to-peak magnetic flux density.  $k$ ,  $\alpha$ , and  $\beta$  are the Steinmetz parameters as used in SE.  $f$  is the excitation frequency, and  $f_{eq}$  is the equivalent frequency calculated through (3).

### 2.2. GSE

The generalized Steinmetz equation (GSE) considers instantaneous power loss depends only on immediate value  $B(t)$  and this form of the equation would not work when  $\alpha > \beta$ , because the iron losses would get infinite. For some materials  $\alpha$  could get larger than  $\beta$ , so GSE cannot be used for these materials. Combining the instantaneous dissipation hypothesis with the SE and GSE is given as follows:

$$P_{GSE} = \frac{k_i}{T} \int_0^T \left| \frac{dB}{dt} \right|^\alpha |B(t)|^{\beta-\alpha} dt \quad (4)$$

$$k_i = \frac{k}{2^{\beta-\alpha} (2\pi)^{\alpha-1} \int_0^{2\pi} |\cos \theta|^\alpha d\theta} \quad (5)$$

### 2.3. IGSE

The improved generalized Steinmetz equation (IGSE) replaces  $B(t)$  of GSE with its peak-to-peak value  $\Delta B$ . In this way, the impact of magnetization history on  $dB/dt$  is also taken into account. The equation is written as follows:

$$P_{IGSE} = \frac{k_i}{T} \int_0^T \left| \frac{dB}{dt} \right|^\alpha |\Delta B|^{\beta-\alpha} dt \quad (6)$$

$$k_i = \frac{k}{2^{\beta-\alpha} (2\pi)^{\alpha-1} \int_0^{2\pi} |\cos \theta|^\alpha d\theta} \quad (7)$$

The IGSE however, is still significantly more complicated to implement than the SE and MSE. As a result, many in the industry continue to use the SE with the Fourier Transform of the non-sinusoidal waveform (FTSE). But due to the non-linearity of the SE, it is inaccurate in the literature [4]. The experiment set-up is discussed in section 3, and the results are displayed in section 4. Conclusions are drawn in section 5.

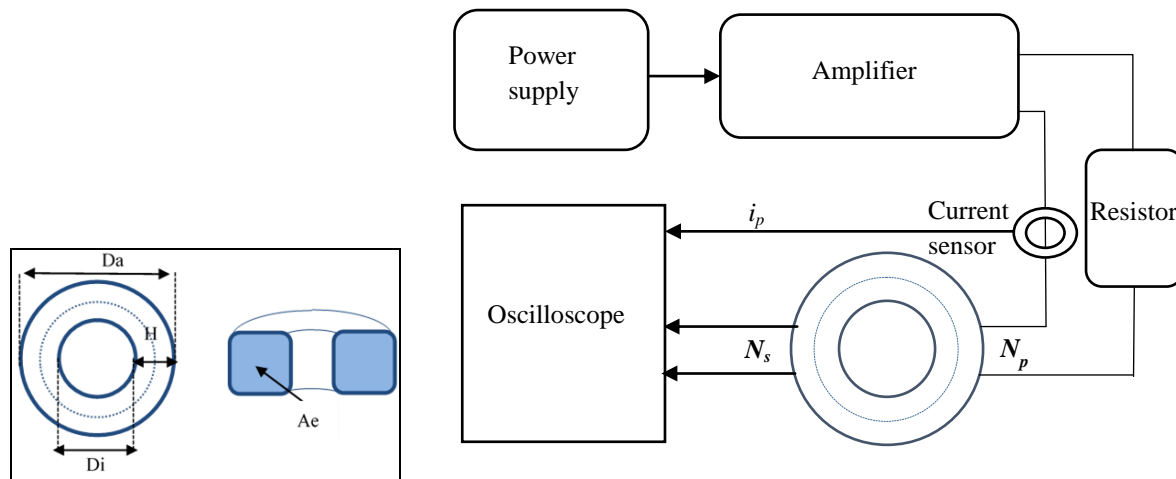
## 3. Experimental setup

For the data measurement, Ferrite (N87) and Nano-crystalline (1K107) ring sample were measured by the arbitrary waveform core loss testing system. Physical data of the ring sample are listed in table 1. Tektronix AFG2021-SC power amplifier was used to generate three test waveforms to investigate how core loss and accuracy changes with harmonics effect. The three test waveforms were created by the amplifier manufacturer's software, Arbexpress software.

**Table1.** Core physical characteristics of Ferrite and Nano-crystalline

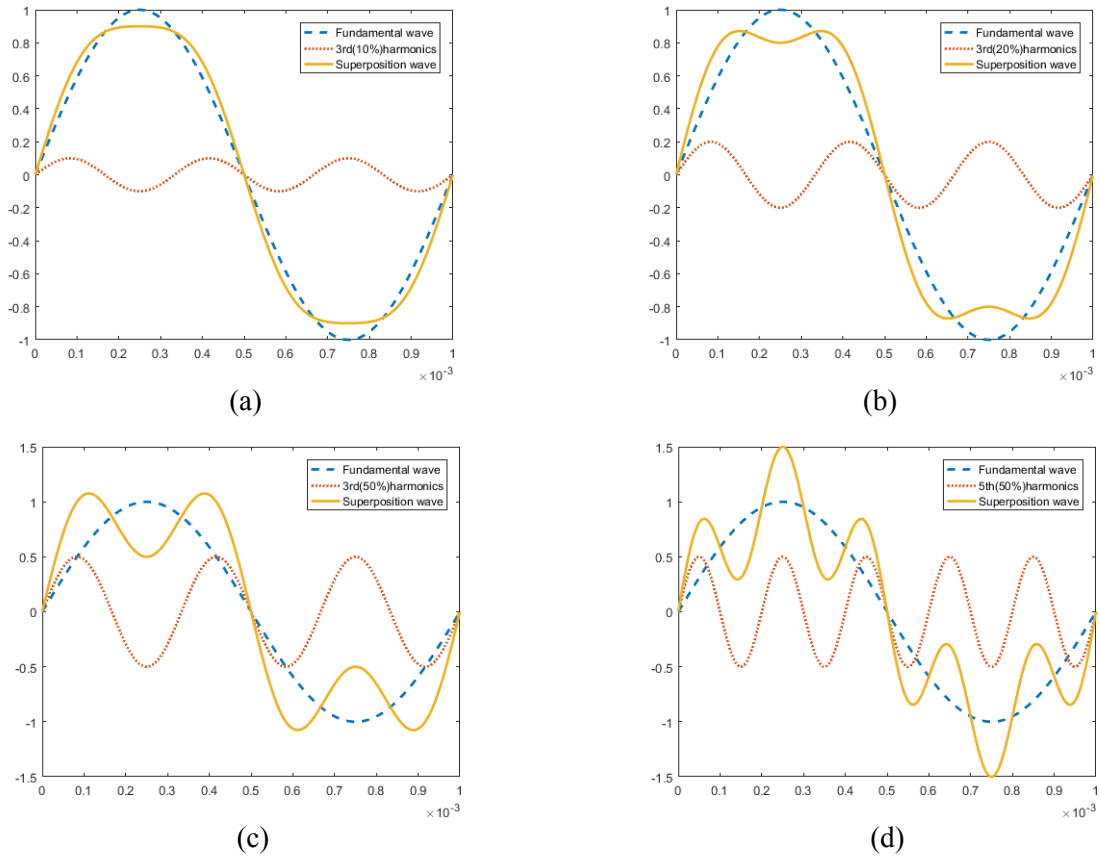
Description	Symbol	value		Unit
		Ferrite	Nano-crystalline	
Outer diameter	$D_a$	41.8	50	mm
Inner diameter	$D_i$	26.2	40	mm
Height	$H$	12.5	20	mm
Effective area	$A_e$	95.75	93.8	mm <sup>3</sup>
Mean magnetic path length	$L_m$	103	141.4	mm
Weight		50	72	g/cm <sup>3</sup>
Grade		N87	1K107	

Two windings were placed around the core under test. Primary winding  $N_p$  for Ferrite was 15 turns, and Nano-crystalline was 8 turns, the secondary winding  $N_s$  was eight and three turns respectively. The oscilloscope was InfiniiVision D50-X. The amplifier excited the primary winding, and the current sensor measured the current and connected with the oscilloscope. Experiment data was collected with USB from the oscilloscope. The core dimensions and the measurement system is shown in Fig 1.



**Figure 1.** (a) Illustration of core dimensions. (b) Sample core measuring set up

The Programmable power supply can provide standard sinusoidal excitation and complex non-sinusoidal excitation. Base on the fundamental frequency 1kHz, the third order harmonics 3kHz and fifth order harmonics 5kHz were added to the fundamental frequency, and the superposition of waveform was obtained. Fig 2, shown that by adding the different order and content of harmonics in the primary waveform. By combining the harmonics effect, the final waveform shape and amplitude was changed depending upon the harmonics order and content. The less content of harmonics can cause a little bit change of fundamental waveform, but the significant content and order of harmonics can create the changing of the original waveform which will indirectly influence the core loss of magnetic materials. The presence of harmonics cause additional loss, temperature rise and more easily reach material saturation. This effect can lead to local heating and affects the operation of the electrical machine.



**Figure 2.** Excitation waveform under different harmonic content (a) Third harmonics, 10% content. (b) Third harmonics, 20% content. (c) Third harmonics, 50% content. (d) Fifth harmonics, 50% content.

By measuring the open circuit secondary voltage, the core losses were considered, allowing the direct calculation of the  $\mathbf{B-H}$  loop. The sample core has two windings. The primary winding is used to create the magnetic field intensity  $\mathbf{H}$ . The magnetic field intensity is given by:

$$H(t) = \frac{N_p i_p(t)}{l_{core}} \quad (8)$$

Where  $N_p$  is the number of turns in the primary winding,  $I_p$  is the current flowing in the primary winding and  $l_{core}$  is the mean magnetic path length of the core. The sense coil winding is used to measure the magnetic flux density  $B$  created by the primary winding current. The induced voltage in the secondary side  $v_s$  is given by:

$$v_s(t) = N_s A_e \frac{dB(t)}{dt} \quad (9)$$

Where  $N_s$  is the number of turns in the secondary winding. Rearranging (10) to solve for the flux density produces:

$$B(t) = \frac{1}{A_e N_s} \int v_s dt \quad (10)$$

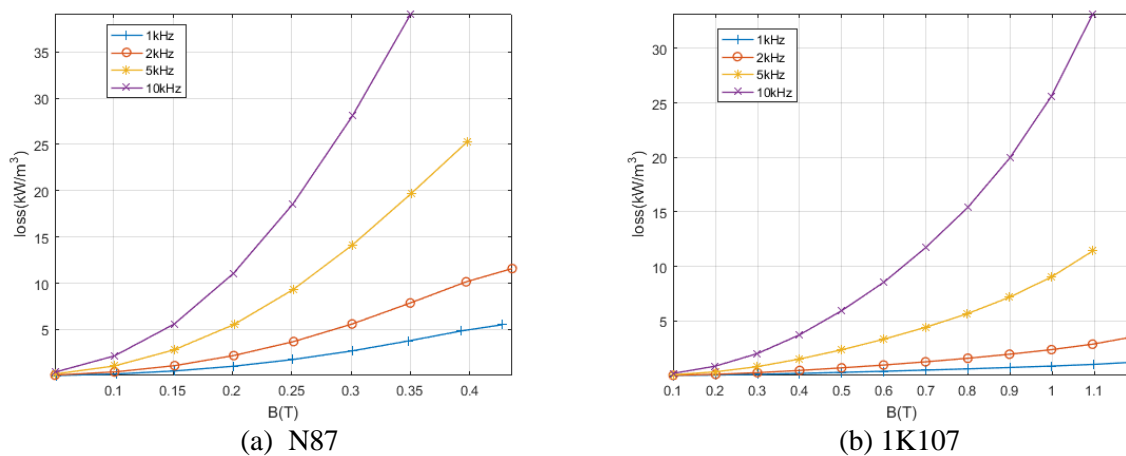
After that, the  $\mathbf{B-H}$  loops are plotted. Based on the core losses separation model [11]. The specific core losses  $P$  (in[W/kg]) can be determined:

$$P = f \frac{A_{BH}}{\rho_{fe}} \quad (11)$$

Where  $f$  is the frequency of excitation voltage,  $A_{BH}$  is the area of the **B-H** loops and  $\rho_{fe}$  is the specific mass density of the testing ring core material.

#### 4. Test results and data analysis

Firstly, both Ferrite and Nano-crystalline materials were excited under sinusoidal with 1kHz, 2kHz, 5kHz, and 10kHz frequencies. According to the data, the core loss, permeability and hysteresis loop could be calculated with Matlab. As the magnetic flux density **B** and frequency increased, the losses increased. When the frequency was over 5kHz, the loss increased was large in both materials is shown in Fig 3. So it means the core loss also depends on the frequency effect.



**Figure 3.** Core loss under sinusoidal excitation with different frequencies

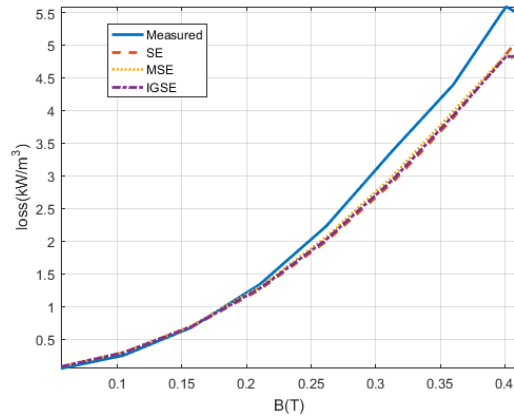
The interest frequency was 1kHz; therefore the system needed to be characterized first to determine its Steinmetz parameters on the 1 kHz. By using the curve fitting in measured data, the Steinmetz parameters can be predicted. The value of  $k$ ,  $\alpha$ , and  $\beta$  for each material under 1kHz frequency is shown in Table 2. For both Ferrite and Nano-crystalline, the losses were calculated using experimentally obtained voltage, current measurements and the estimated Steinmetz parameters in three empirical methods; the standard SE, the MSE, and the IGSE. The measurements and calculations were repeated for three waveforms: 20% third order harmonics, 50% third order harmonics and 50% fifth order harmonics. The results are shown in Fig 4.

**Table 2.** Steinmetz parameters

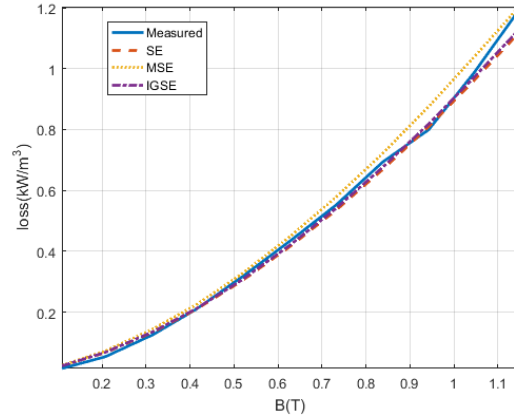
Material	$k(\text{kW/m}^3)$	$\alpha$	$\beta$	frequency
Ferrite (N87)	0.4893	0.6126	2.103	1kHz
Nano-crystalline (1K107)	0.2663	0.1758	1.646	1kHz

In Ferrite the saturation flux density was more than the 0.4T under sinusoidal excitation but higher the harmonics order and content, it had reached saturation with less than the flux density 0.4T. All the empirical methods results were the same with measured data when the flux density was between the 0 to 0.2T. After 0.2T, the results differed from the measured data. Similarly, in Nano-crystalline, the flux density was less than the 1T under the high harmonics effect, all the empirical methods were mostly same with measured data, but the IGSE gave the better results than the SE and MSE. MSE gave more error percent than the other ways. Both of these materials are used in power electronics for high frequency. So the base excitation frequency 1kHz and the third order frequency 3kHz, fifth order frequency 5kHz may not be enough for these materials. Moreover, according to the calculated **B-H** loop, there was no minor loop and sub-loop in the flux density **B** waveforms. If there were minor and

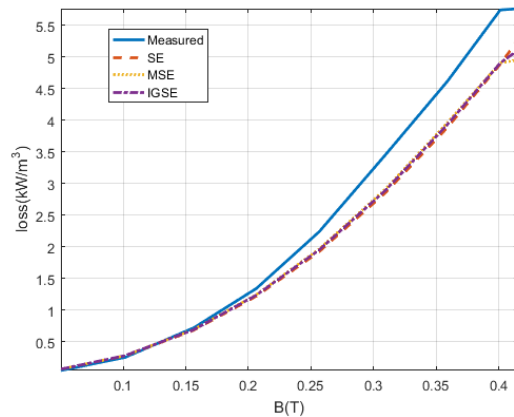
sub-loop, core loss calculation for IGSE must be calculated for each loop, and it would give more accurate results.



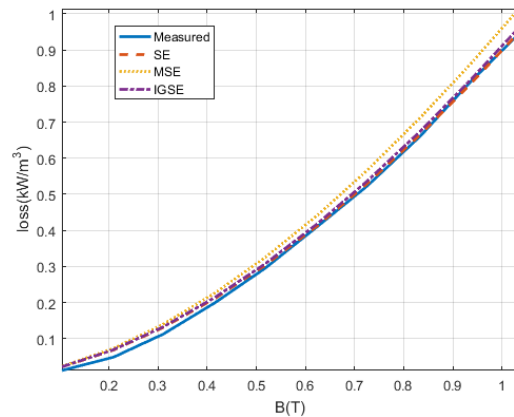
(a) 3<sup>rd</sup> order 20% content in N87



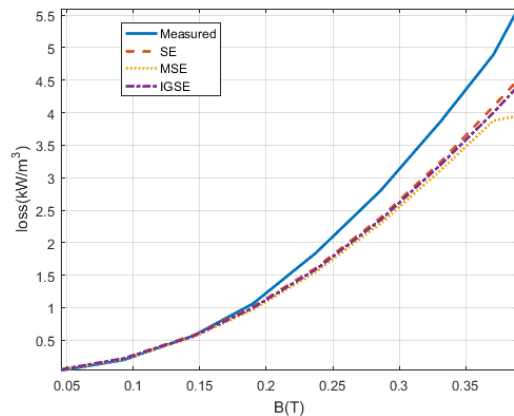
(b) 3<sup>rd</sup> order 20% content in 1K107



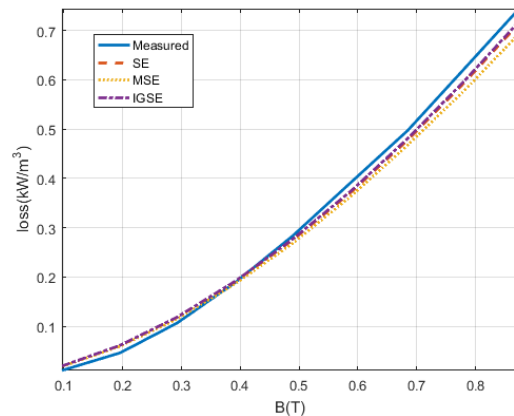
(c) 3<sup>rd</sup> order 50% content in N87



(d) 3<sup>rd</sup> order 50% content in 1K107



(e) 5<sup>th</sup> order 50% content in N87



(f) 5<sup>th</sup> order 50% content in 1K107

**Figure 4.** Compare core loss calculation in ferrite N87 and Nano-crystalline 1K107 under different harmonics order and content

## 5. Conclusion

The influence of harmonics effect on core loss and calculation of core loss using the empirical equation, i.e., SE, MSE, and IGSE on the soft magnetic ring core is presented in this paper. The order and content of harmonics effect play important roles according to the core loss analysis. The high



harmonics effect can easily cause material saturation and make temperature rise and vibration; it can cause additional losses in the electrical machine. The Steinmetz Equation is used extensively in industry in conjunction with a Fourier Transform to calculate losses in non-sinusoidal excited transformer cores. For non-sinusoidal excitation, the MSE and IGSE are more suitable than the SE. In this experiment, it does not show the minor loop in the  $B$ - $H$  loop because the harmonics effect was not much active. If the minor loop condition happens, the IGSE will give better results than the SE and MSE. Overall the IGSE was found to be the most accurate; it is therefore recommended for highly non-sinusoidal flux density waveforms. However, the harmonics effect and core loss calculation using the empirical methods of material samples are analyzed, which can provide the reference for improving the efficiency of the electrical machine.

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