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Iron Loss Analysis Considering Excitation Conditions Under Alternating Magnetic Fields

Sun-Ki Hong* · Chang-Seop Koh

Abstract

In this paper, the nature of iron loss in electrical steel during alternating field excitation is investigated more precisely. The exact definition of AC iron loss is cleared by accurately measuring the iron loss for conditions of both the sinusoidal magnetic field and sinusoidal magnetic flux density. The results of this approach to iron loss calculations in electrical steel are compared to experimentally-measured losses. In addition, an inverse hysteresis model considering eddy current loss was developed to analyze the iron loss when the input is the voltage source. With this model, the inrush current in the inductor or transformer as well as the iron loss can be calculated.

Key Words : Iron Loss, Alternating Magnetic Field, Inverse Hysteresis Model, Eddy Current

1. Introduction

For a precise design and analysis of electric machines, iron loss analysis is one of the most important elements [1]. However, if sinusoidal magnetic field intensity is applied to magnetic material, the resulting flux density is non-sinusoidal, containing harmonics because of hysteresis. However, iron loss in electrical steel is defined under sinusoidal flux density conditions, meaning that the magnetic field intensity must be non-sinusoidal because of hysteresis and eddy current effects. The iron loss in these two cases is not identical, but this fact has received almost no attention to date. One approach [2] for including harmonics in the iron loss analysis uses Discrete Fourier Transformation (DFT) to decompose the flux density into its harmonic components. The iron loss at each frequency is then calculated using an iron loss data sheet, and the total loss is obtained by summation of the iron loss from all of the elements. However, the results of this approach can be too large in comparison to the actual iron loss. The purpose of this research is to investigate more closely the nature of iron loss in electrical steel during alternating field excitation. In this paper, the exact definition of the AC iron loss is conformed by accurately measuring the loss for conditions of both sinusoidal H and sinusoidal B. The results of this approach to iron loss calculations in electrical steel

* Main author : Professor, Department of System Control, Hoseo University
Tel : +82-41-540-5674, Fax : +82-41-540-5587
E-mail : skhong@hoseo.edu
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are compared to experimentally-measured losses. In addition, an inverse magnetization-dependent hysteresis model considering eddy current loss is developed to analyze the iron loss when the input is the voltage source. With this model, the inrush current in the inductor or transformer as well as the iron loss can be calculated.

2. Iron Loss for Alternating Magnetic Fields

2.1 Hysteresis loss

Hysteresis loss is the *B-H* loop area not including the eddy current loss by applying the lowest frequency. Fig. 1 shows the soft bulk iron toroidal winding in this experiment. The outer and inner diameters are 50 and 40[mm]. The height is 7[mm]. Fig. 2 shows the two kinds of *B-H* loops of the bulk ring, whose areas represent iron loss for the input of 0.2[Hz]. The dotted line shows the loop whose input is the magnetic field intensity and the output becomes the magnetic flux density. This was called the sin*H* condition loop, meaning that the input *H* is sinusoidal. The solid line is sin*B* loop, and the sinusoidal flux density *B* becomes the input. To accomplish these experiments, the apparatus shown in Fig. 3 is developed and the shapes of *H* or *B* can be controlled. As can be seen in Fig. 2, the loop shapes are different, which means the losses are different according to the measuring condition. Under the sin*B* condition, there are no harmonics of flux density, therefore eddy current losses do not exist except for the fundamental frequency loss. However, under sin*H* condition, the flux density has harmonics, and they make EMFs that cause harmonic eddy current losses. This effect makes the *B-H* loop larger than that under the sin*B* condition even though the applied frequency is very low.

Fig. 1. Toroidal winding specimen

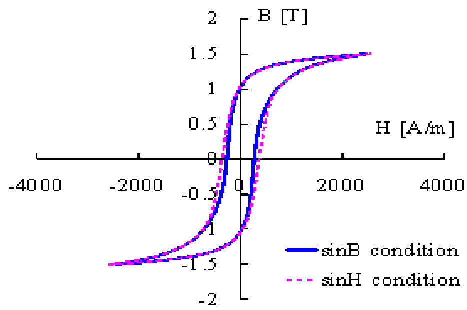


Fig. 2. *B-H* loops under sin*B* and sin*H* conditions

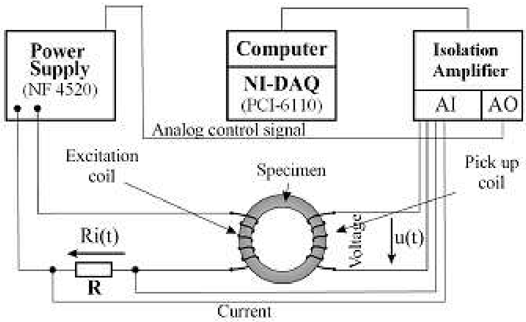


Fig. 3. Measurement system

As a result, the hysteresis loss needs to be measured under the sinusoidal flux density condition.

2.2 Iron loss with harmonics

The current of exciting coil and flux density can be measured with the measurement system in Fig. 3; the input shape of *H* or *B* can be controlled by feedback. Fig. 4 shows the measured *B-H* loop (solid line) under sin*H* condition and the other separated loops according to their frequencies by FFT. As can be seen in the figure, the fundamental frequency loop (dotted line, 1st B) is larger than the original loop (all B). This means the iron loss cannot be calculated by the summation of each frequency component and it must be calculated by measuring the loop area. If the B-H data are known or measured, the loss can be calculated by integrating the magnetic field intensity with the flux density [3].

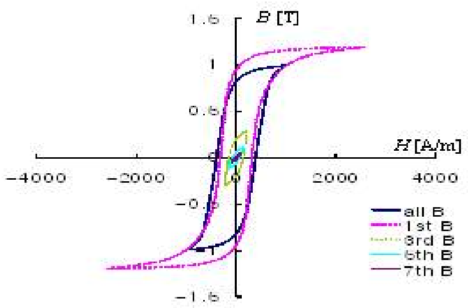
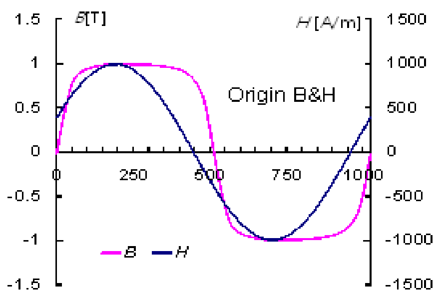
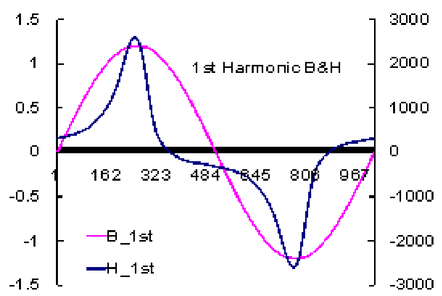


Fig. 4. Original and harmonic loops



(a) B waveform under sinH



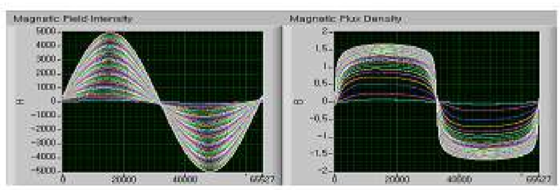
(b) H waveform for 1st B waveform

Fig. 5. B and H waveforms

Fig. 5 shows the B and H waveforms of the loops in Fig. 4. Fig. 5 (a) shows the original B and H waveforms, and the waveform of B is not sinusoidal, which means it would have harmonics. Fig. 5 (b) shows the H waveforms when B is the 1st harmonic, which means the waveform of B is sinusoidal. The peak value of B and H is bigger than that of the original B and H.

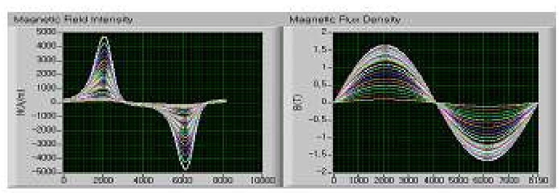
Table 1. Measured and FFT loop results for Fig. 4

	Freq.	Bm[T]	Loss/ 1 peroid	Total Loss
Original B	1[Hz]	0.993149	0.186105	0.186105
FFT 1st	1[Hz]	1.196438	0.232240	0.494115
3rd	3[Hz]	0.289885	0.049908	
5th	5[Hz]	0.114318	0.014979	
7th	7[Hz]	0.049945	0.004099	
9th	9[Hz]	0.020309	0.000801	
11th	11[Hz]	0.006875	0.000123	



(a) Magnetic field intensity (b) Magnetic flux density

Fig. 6. Experiment results under sinH

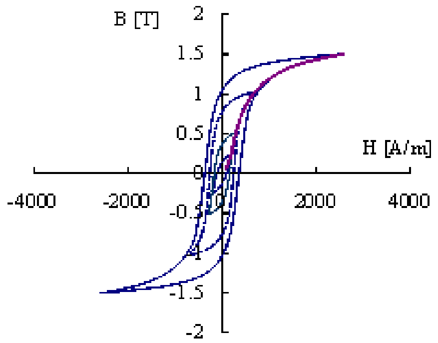


(a) Magnetic field intensity (b) Magnetic flux density

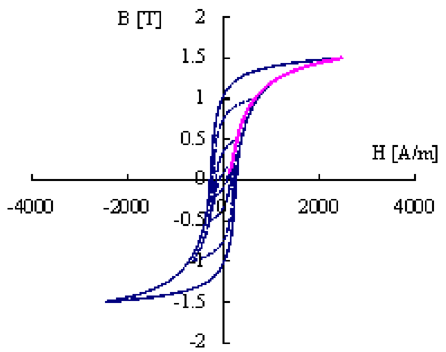
Fig. 7. Experiment results under sinB

Table 1 shows the measured and FFT loop results for Fig. 4. Fig. 6 and 7 show the waveforms measured by the developed measuring device in Fig.

3. Fig. 6 (b) shows the flux density waveforms when the applied field is sinusoidal (Fig. 6 (a), sin$H$ condition).



(a) B-H loops under sin$H$ condition



(b) B-H loops under sin$B$ condition

Fig. 8. B-H loops under different conditions

Fig. 7 shows those things under sin$H$ condition. As can be seen in the figures, the measured results are different according to the input conditions. In Fig. 6 (b), the flux density looks like square waves, so they include lots of harmonics and increased iron loss because the eddy current loss is increased. Fig. 8 shows minor loops under sin$H$ and sin$B$ conditions. As expected, the loops in Fig. 8 (a) are a little thicker and the loop area is larger than that in Fig. 8 (b). Fig. 9 shows the losses under sin$H$ and sin$B$ conditions. The loss under sin$H$ is larger than that under sin$B$ when the flux density is increased.

Fig. 10 shows the initial magnetization curves according to the applied source frequency. The reason for the difference is the definition of the curve. In this case, the each point is determined by B when H is at a maximum. They would be the same if the points were determined with H when B is at a maximum.

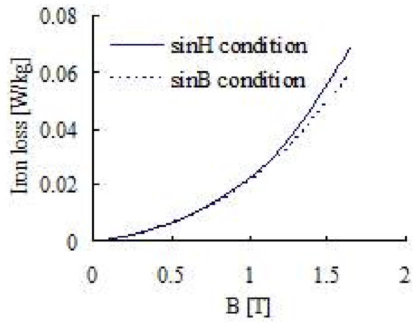


Fig. 9. Iron loss under sin$H$ and sin$B$ conditions according to flux density

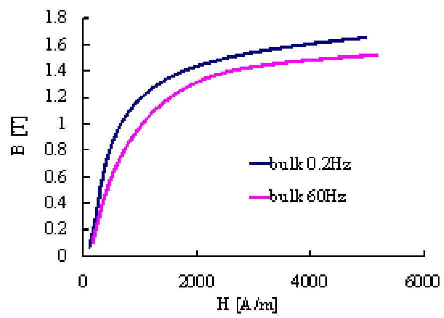


Fig. 10. Initial magnetization curves according to the applied source frequency

3. Inrush current calculation

The Preisach model is well known as a good hysteresis model. The input is H and the output is B in the Preisach model. In many cases, the input is not the current but the voltage source, and then the input element for iron loss calculation needs to be magnetic flux density. Therefore, the inverse hysteresis model $H = f^{-1}(B)$ is required.

If the flux density $B(H)$ changes, by changing the magnetic field intensity with ΔH, $B(H)$ can be determined in the Preisach model. To reduce calculation error, the interpolation method is used. For example, if $B(t_p) > B(t_{p-1})$ and the exact value $B(t_p)$ is between the two calculated flux densities where p is a time step, $H(t_p)$ can be calculated as follows.

$$H(t_p) = H_2\frac{B(t_p)-B_1}{B_2-B_1} + H_1\frac{B(t_p)-B_2}{B_1-B_2} \quad (1)$$

The inverse model is as follows when the final time step is p = N and $B(H)$ is calculated using the magnetization-dependent hysteresis model [4].

Step 0 : at time step p = 0, let H_1 = 0, H_2 = 0,
B_1 = 0, B_2 = 0, final time step N
Step 1 : at time step p, flux density is $B(t_p)$.
Step 2 : if $B(t_p) < B(t_{p-1})$, goto Step 5.
Step 3 : for $H_2 \leftarrow H_2 + \Delta H$, find $B_2 = B(H_2)$.
Step 4 : if $B_2 \leq B(t_p)$, $B_1 \leftarrow B_2$ and goto Step 4 else goto Step 7
Step 5 : for $H_2 \leftarrow H_2 - \Delta H$, find $B_2 = B(H_2)$.
Step 6 : $B_1 \leftarrow B_2$, goto Step 5.
Step 7 : calculate $H(t_p)$ from Eq. (1).
Step 8 : if $p < N-1$,
$p \leftarrow p+1$, $H_2 \leftarrow H(t_p)$, $H_1 \leftarrow H_2$
and goto Step 2 else end

The inverse algorithm is applied to a series R-L circuit. The voltage equation becomes like (2) where the applied voltage is sinusoidal.

$$n\frac{d\phi}{dt} + r \cdot i = E_m \sin(\omega \cdot t + \theta) \quad (2)$$

By solving this equation for flux ϕ, and transforming it to a discrete equation, it becomes like (3).

$$\phi(k+1) = \phi(k) + \frac{\Delta t}{n}\left[E_m \sin(\omega t_k + \theta) - ri\right] \quad (3)$$

Where k is time step, n is the number of turns of the ring core and θ is the phase angle of voltage. Fig. 11 shows the measured transition curves of the tested material to apply to the Preisach model.

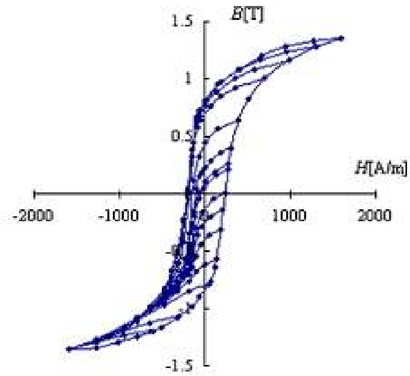
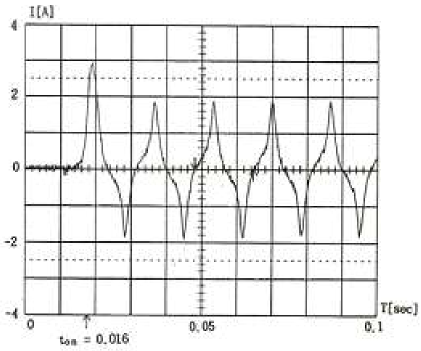


Fig. 11. Transition curves of tested material

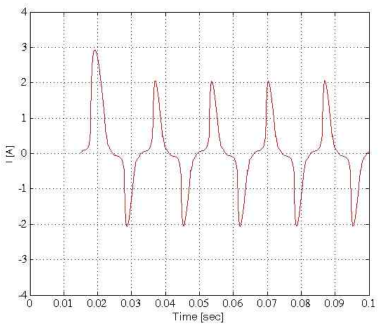
The eddy current loss can be calculated with (4) where δ is the thickness of the steel, w is the width and ρ is the electrical resistivity. Eddy current i_e can be calculated because P_e can be calculated with (4) and the applied voltage is known. The total current is calculated by adding i_e to i in (3).

$$P_e = \frac{1}{\delta w}\int_V \rho J^2 dV = \frac{1}{\delta w}\int_{-\frac{\delta}{2}}^{\frac{\delta}{2}} \rho\left(\frac{x}{\rho}\frac{dB}{dt}\right)^2 wx\,dx$$
$$= \frac{\delta^2}{12\rho}\left(\frac{dB}{dt}\right)^2 \quad (4)$$

Fig. 12 shows the measured and simulated current waveform results.



(a) Measured current wave form



(b) Simulated current waveform

Fig. 12. Inrush current waveforms in an inductor

4. Conclusion

In this paper, the definition of iron loss under alternating magnetic fields is conformed by measuring the exact iron loss. The iron loss needs to be measured under the sinusoidal flux density condition. In addition, the iron loss including harmonics is measured by experimentation and analyzed. As a result, the iron loss must be calculated by the real B-H loop area. For application, the inverse hysteresis model is applied to the inductor core and the inrush current is experimented with and simulated considering eddy current loss.

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Biography

Sun-Ki Hong

Sun-Ki Hong was born in Seoul, Korea, on January 24, 1965. He graduated from the Department of Electrical Engineering, Seoul National University in 1987. He received his M.S. and Ph.D in electrical engineering from Seoul National University in 1989 and 1993, respectively. He became a member of IEEE in 1993 and worked as a researcher at REX Industrial Co., Ltd. from 1993 to 1995. He has been teaching at the School of Electrical Engineering, Hoseo University since 1995. His special interests include the modeling and computation of hysteresis and present interests are the fields of design and analysis of electric and field analysis of magnetic field systems with the finite element method considering hysteresis.

Chang-Seop Koh

Chang Seop Koh received B.S., M.S. and Ph.D. degrees in Electrical Engineering from Seoul National University in 1986, 1988 and 1992, respectively. He was a visiting researcher in the department of ECE at Florida International University from 1993 to 1994 and visiting scholar in the department of EE at Texas A&M University from 2003 to 2004. He was also a senior researcher at the Central R&D Center, Samsung Electro-mechanics Co. Ltd. from 1994 to 1996. He is currently a professor at the School of Electrical and Computer Engineering, Chungbuk National University, Cheongju, Korea. His research interests cover the design of electric machines and electromagnetic actuators, and optimum design of electromagnetic devices using the finite element method.