Journal of Applied Physics

Iron loss prediction under pulse width modulated conditions

I. A. J. Moses and J. Leicht

Citation: J. Appl. Phys. **97**, 10R507 (2005); doi: 10.1063/1.1854432
View online: http://dx.doi.org/10.1063/1.1854432
View Table of Contents: http://jap.aip.org/resource/1/JAPIAU/v97/i10
Published by the American Institute of Physics.

Additional information on J. Appl. Phys.

Journal Homepage: http://jap.aip.org/
Journal Information: http://jap.aip.org/about/about_the_journal
Top downloads: http://jap.aip.org/features/most_downloaded
Information for Authors: http://jap.aip.org/authors

ADVERTISEMENT

Downloaded 02 Apr 2012 to 131.251.133.28. Redistribution subject to AIP license or copyright; see http://jap.aip.org/about/rights_and_permissions

HTML ABSTRACT + LINKS

JOURNAL OF APPLIED PHYSICS **97**, 10R507 (2005)

Iron loss prediction under pulse width modulated conditions

I. A. J. Moses and J. Leicht
Wolfson Centre for Magnetics Technology, School of Engineering, Cardiff University, P.O. Box 925, Cardiff CF24 0YF, Wales, United Kingdom

(Presented on 9 November 2004; published online 17 May 2005)

This paper illustrates the state of art of magnetic testing of electrical steels under distorted flux wave forms, gives comparisons of performance of various motor steels and introduces a loss prediction approach based on the linear relationship between iron loss produced under sinusoidal flux and that produced under pulse width modulated (PWM) excitation. Results are very promising showing agreement between measured and predicted losses in a wide range of electrical steels magnetized under various PWM wave forms to within 5%. © *2005 American Institute of Physics*.
[DOI: 10.1063/1.1854432]

I. INTRODUCTION

The increase of losses in electrical steels due to nonsinusoidal excitation wave form has been well known for many years. Recently the growing use of inverters to supply rotating machines with pulse width modulated (PWM) voltages has increased its importance. A significant number of publications have appeared showing loss increases but there are conflicting results and some ambiguity due to incomplete definitions of magnetizing conditions as well as possible variation of modulation techniques and parameters although some trends have been well documented by several authors.[1,2] In this paper a linear relationship between the losses of nonoriented electrical steels containing 0.2%–6.5% silicon measured under sinusoidal and PWM flux conditions is reported. This characteristic is described by a linear regression model which makes it possible to predict losses in similar materials over a wider magnetization range. Losses were measured using a universal loss measurement system which included facility for producing the highly distorted controlled PWM flux wave shapes.

II. EXPERIMENTAL RESULTS

Measurements were carried out on Epstein strips of fully processed, nonoriented electrical steel, comprising a group 0.5 mm thick with 0.2%, 0.3%, 1.3%, 1.8%, 3.0%, and 4.0% silicon content. These samples were excited with square, PWM, and sinusoidal voltage wave forms.

The material was magnetized and its iron loss and permeability was measured making use of a Universal A.C. Measurement System.[3] Under sinusoidal flux conditions, the material was magnetized from 50 to 200 Hz up to 1.5 T. Under PWM input conditions, the material was tested over the same fundamental frequency and peak flux density ranges at frequency ratios (carrier frequency divided by the modulating signal frequency) of 12, 15, and 48, and modulation index (modulating signal amplitude divided by the carrier amplitude) in the range 0.5–1.0.

The specimen was characterized under sinusoidal flux density, in accordance with the IEC Standard,[4] in order to make measurements, which may be conveniently reproduced. The source voltage was adjusted and flux density obtained from the average rectified value of the secondary $\overline{U_2}$ given by

$$\overline{U_2} = 4 \cdot f \cdot N_2 \cdot A \cdot \hat{B}, \tag{1}$$

where f is the fundamental frequency (Hz), N_2 the number of turns of the secondary winding, A the cross-sectional area of the test specimen (m^2), and $\hat{B}$ the peak value of the intrinsic magnetic flux density (T). The harmonics of the induced voltage wave form were controlled, using a analog negative feedback technique, to be less than 3% of the fundamental during all measurements.

Under pulse width modulation wave form excitation, a digital oscilloscope was used to obtain the integrated wave form from the measured secondary voltage. The peak flux density $\hat{B}$ using this method is given by

$$\hat{B} = \frac{e_{pp}}{2N_2A}, \tag{2}$$

where e_{pp} is the peak to peak value of the integrated signal.

Figure 1 shows the variation of specific total loss with silicon content in 0.5 mm thick material under sinusoidal and PWM voltage excitation at 50 Hz fundamental frequency and peak flux density 1.5 T.

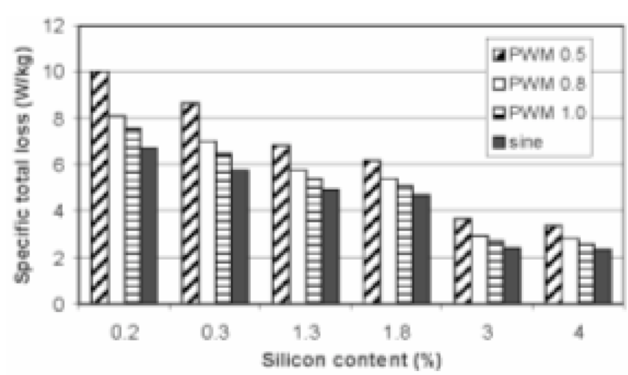

FIG. 1. Variation of total loss with silicon content under sinusoidal and PWM voltage excitation at 50 Hz fundamental frequency and peak flux density 1.5 T.

 © 2005 American Institute of Physics

Downloaded 02 Apr 2012 to 131.251.133.28. Redistribution subject to AIP license or copyright; see http://jap.aip.org/about/rights_and_permissions

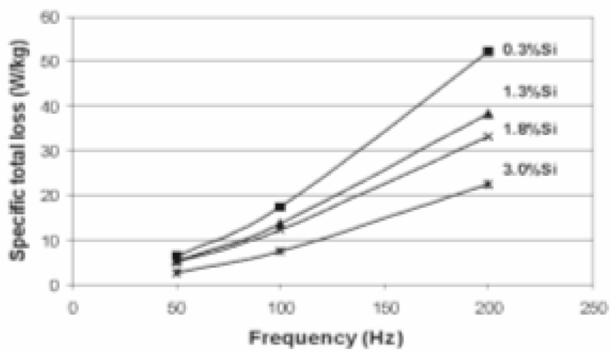

FIG. 2. Variation of specific loss with fundamental frequency in 0.5 mm thick materials with 0.3% to 3.0% silicon under PWM excitation. (1.5 T, modulation index=1.0, frequency ratio=12).

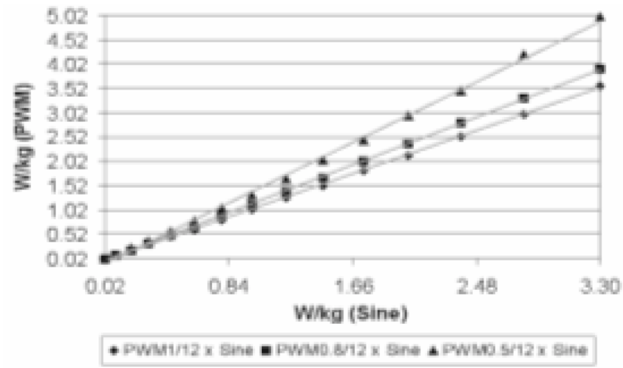

FIG. 4. Variation of specific total loss under PWM excitation with the specific total loss under sine excitation in 3% silicon 0.65 mm thick nonoriented electrical steel (as in Fig. 3).

In all cases the reproducibility error was less than 0.5%. The specific loss in the 4% silicon sample was around 65% of the loss in the 0.2% silicon material under sinusoidal and PWM excitation. Under PWM excitation the specific power loss was 12%, 20%, and 45% higher at modulation indices of 1.0, 0.8, and 0.5 respectively, than that under sinusoidal excitation of the same peak flux density and fundamental frequency.

Figure 2 shows the variation of specific loss with frequency in batches of 0.3%, 1.3%, 1.8%, and 3.0% silicon under PWM excitation with modulation index and ratio of 1.0 and 12, respectively, at 1.5 T peak flux density. As expected, the loss increases rapidly with frequency. The loss is 550%–725% higher in the different materials at 200 Hz compared to 50 Hz.

III. LOSS PREDICTION APPROACH

In all measurements it was observed that the loss under PWM and sinusoidal flux conditions varied in a similar manner for the same material thickness, silicon content, frequency and peak flux density. Figures 3 and 4 show such linear correlation found in two materials. The slopes of the graphs depend on the harmonics present in the different PWM wave forms and can be used to build up relationships between loss under PWM and sinusoidal flux density for different materials. With this in mind an approach was developed to predict iron loss based on this linear relationship.

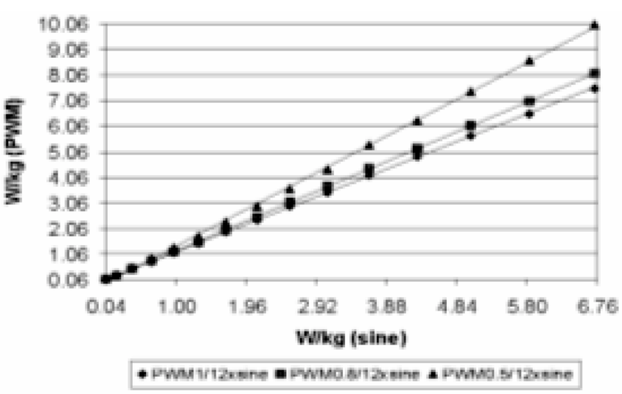

FIG. 3. Variation of specific total loss under PWM excitation with the specific total loss under sine excitation in nonoriented electrical steel 0.2% 0.5 mm thick in the range 0.1 T to 1.5 T.

Equation (3) is the linear representation of the variation. The coefficients A (slope) and B (interception of y axis) at the same harmonic distortion vary linearly and polynomially (second order), respectively, with frequency as shown in Eqs. (4) and (5) as follows:

$$P_{PWM} = A \cdot P_{Sine} + B, \tag{3}$$

$$A = C \cdot f + D, \tag{4}$$

$$B = E \cdot f^2 + F \cdot f + G. \tag{5}$$

The coefficients C and D in Eq. (4) and the coefficients E, F, and G in Eq. (4) can be represented in terms of a polynomial (second order) variation with total harmonic distortion (THD). In theory B [in Eq. (3)] is zero if the origin of the graphs in Figs. 3 and 4 is set at 0.0 T but in this case the origin on the x scale is 0.01 T hence finite values of B do occur. The coefficients were obtained for each material considering their grade (silicon content and thickness) variation. In Table I the final equation for the nonoriented electrical steel 0.2% Si, 0.5 mm thick is presented.

In Tables II and III the performance of the approach is shown considering some data points not included and others included in the development of the equation, respectively.

The agreement between predicted and measured data is very close for the two materials when comparing values included or not included in the development of the coefficients in the equations. Similar agreement was obtained with the other materials and subsequent analysis to be reported in

TABLE I. Polynomial equations of coefficients C, D, E, F, and giving G their variation with the total harmonic distortion (THD) in 0.2% Si, giving nonoriented electrical steel.

$P_{PWM}=(C\cdot f+D)\cdot P_{Sine}+(E\cdot f^2+F\cdot f+G)$	
C	$5.292\times10^{-3}\cdot \text{THD}^2-4.325\times10^{-3}\cdot \text{THD}+8.966\times10^{-4}$
D	$2.879\times10^{0}\cdot \text{THD}^2-2.539\times10^{0}\cdot \text{THD}+1.674\times10^{0}$
E	$2.123\times10^{-4}\cdot \text{THD}^2-2.866\times10^{-4}\cdot \text{THD}+8.935\times10^{-5}$
F	$1.259\times10^{-2}\cdot \text{THD}^2-1.544\times10^{-2}\cdot \text{THD}+3.794\times10^{-3}$
G	$3.521\times10^{-2}\cdot \text{THD}^2-4.155\times10^{-2}\cdot \text{THD}+1.219\times10^{-2}$

Downloaded 02 Apr 2012 to 131.251.133.28. Redistribution subject to AIP license or copyright; see http://jap.aip.org/about/rights_and_permissions

TABLE II. Percentage difference between measured and predicted losses under PWM excitation in 0.2% and 1.8% silicon content, 0.5 mm thick where data points were not included in development of equations.

B (T)	*f* (Hz)	THD (%)	PWM measured (W/kg)	PWM calculated (W/kg)	Error (%)
Nonoriented 0.2% Si, 0.5 mm					
1.5	50	0.67	8.58	8.62	0.5
1.5	50	0.59	7.96	7.95	0.2
1.0	50	0.67	3.91	3.90	0.2
Nonoriented 1.8% Si, 0.5 mm					
1.5	50	0.67	5.48	5.65	3.0
1.5	50	0.59	5.26	5.32	1.2
1.0	50	0.67	2.54	2.62	2.9

TABLE III. Percentage difference between measured and predicted losses under PWM excitation in 0.2% and 1.8% silicon content, 0.5 mm thick where data points were included in the development of the equations.

B (T)	*f* (Hz)	THD (%)	PWM measured (W/kg)	PWM calculated (W/kg)	Error (%)
Nonoriented 0.2% Si, 0.5 mm					
1.0	50	0.79	4.37	4.60	4.9
1.3	100	0.61	16.21	16.06	0.9
1.5	200	0.47	57.26	57.60	0.6
Nonoriented 1.8% Si, 0.5 mm					
1.0	50	0.79	2.80	2.90	4.2
1.3	100	0.61	9.8	9.8	0.9
1.5	200	0.47	33.5	33.5	0.9

detail in the future shows the method works equally well for nickel iron alloys and cobalt based amorphous material.

IV. CONCLUSION

The linear relationship between loss under sinusoidal and PWM excitation can be used to develop a mathematical method of loss prediction in electrical steels with differences between measured and calculated losses under PWM excitation being generally far less than 5% for a wide range of silicon contents and THD. This is believed to be a simple approach which is sufficiently accurate for material manufacturers or machine designers to use when predicting losses in electrical steel lamination magnetized under severely distorted conditions.

ACKNOWLEDGMENTS

A.J.M. and J.L. are grateful to the EPSRC for Grant No. GR/R82869 and Platform Grant No. GR/R10493/01 which supported the experimental part of this work.

[1]M. Amar and F. Protat, IEEE Trans. Magn. **30**, 942 (1994).
[2]A. Boglietti, A. Cavagnino, M. Lazzari, and M. Pastorelli, IEEE Trans. Magn. **39**, 981 (2003).
[3]P. Anderson, A. J. Moses, and J. Leicht, *UK Magnetic Society Seminar*, Warwick, 2000 (unpublished).
[4]*Methods of Measurement of the Magnetic Properties of Electrical Steel Sheet and Strip by Means of an Epstein Frame* (IEC, Genève, Switzerland, 1996).

Downloaded 02 Apr 2012 to 131.251.133.28. Redistribution subject to AIP license or copyright; see http://jap.aip.org/about/rights_and_permissions