A Complete Model of Iron Losses Prediction in Electric Machines Including Material measurement, Data Fitting, FE Computation and Experiment Validation

Zhao Haisen[1] *Student member, IEEE*, Luo Yingli[1], Ren H. Wang[2] *Fellow, IEEE*, and Peter Baldassari[3] *member, IEEE*
[1]School of Electrical and Electronic Engineering, North China Electric Power University, Beijing, 102206, China
[2]Stanley Black & Decker Corporation, Towson, MD 21286, USA
[3]MagneForce Software System Inc. 5655 South Park Ave Hamburg, NY 14075, USA

Abstract— This paper presents a complete process & model for predicting the iron losses in electric machines. The method includes material measurement, data fitting for loss coefficient determination, FE computation and experimental validation. The model is based on the loss separation of hysteresis and eddy-current losses. Also a new fitting method for obtaining material loss coefficients for FE analysis is derived from the tested specific core losses of a steel lamination ring sample. The generality of the completed method is further verified by application to different steel types and machines. The results predicted by the model showed excellent agreement with the tested data for a high speed PM DC and a PM BLDC machine.

I. INTRODUCTION

It is necessary for electrical machine designers to predict the iron losses accurately in advance, particularly in the development of premium motors. As a result, the model for iron losses prediction in electric machines is always an intensely researched topic. One of the widely known models is the three term model with constant coefficients in [1]. In this model the iron losses are separated into three parts, hysteresis loss, eddy current loss and excess loss. The accuracy and range of application of iron loss models such as these has remained a challenge. The accumulated error in the process of iron loss computation may, in some cases, reach as high as 30% [2]. Some improved models with increased complexity were studied [2-5] and although they represent an improvement in the process of iron loss prediction, none has yet been able to predict iron losses for a wide range of machines with reasonable accuracy.

The aim of this paper is to present a model and a process for iron loss prediction in electric machines, in which the material measurement, data fitting for loss coefficients, FE computation and experimental validation are included completely. The material loss description is based upon the traditional two terms, eddy current and hysteresis losses. The so-called anomalous or excess loss is included automatically in the data processing of the tested cores. A new fitting method for loss coefficients is presented in this paper and finally the predicted results are compared with actual iron loss experimental tests of two different motors. The predicted iron losses agree well with the experimental ones.

II. MATERIAL MEASUREMENT

A. Test Bench Description

To begin the test procedure the lamination core ring is selected with the following specifications, shown in Fig. 1.

- Lamination sheet cut into a ring measuring: 65 mm O.D., 45 mm I.D., and a stack up to 10-11mm high.
- Measure the height of the stack in 0.01 mm increments while exerting 20 kg of pressure on the stack.
- Weigh the net weight of the stack in 0.1 gram increments.

Further, the Brockhaus Messtechnik MPG 100D & MPG Expert DC/AC model [6] is adopted for testing the losses and the test bench is given in Fig. 2. The main characteristics of the measurement system are as follows:

- High accuracy and repeatability.
- Sinusoidal flux density waveform.
- Large scale field strength and polarization.

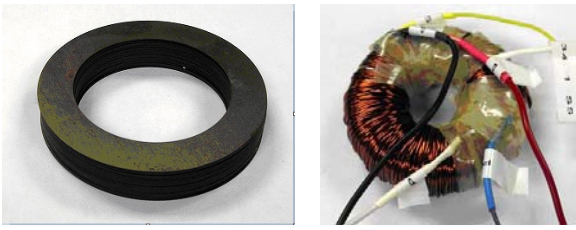

Fig. 1. Appearance of measured steel lamination ring core and coils

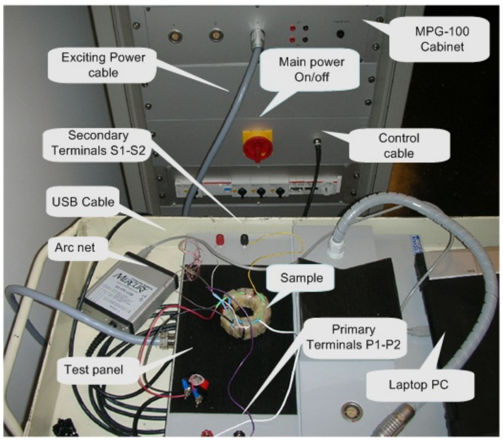

Fig. 2. Test platform of the special core loss

B. Measured Specific Core Loss

The specific core losses of steel EMP33 where measured and the characteristics are given in Table I while the measured losses are shown in Fig. 3.

TABLE I DETAILS OF THE LAMINATION STEELS

Material Type	EMP33
Thickness(mm)	0.5
conductivity(s/m)	2.5×10^{6}
Density(kg/m^3)	7850
Flux density at 5000A/m(T)	1.6054
Core loss at 1.5 T and 50Hz (W/kg)	4.1

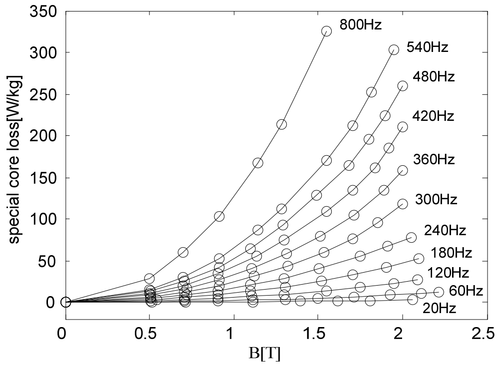

Fig. 3. Tested special Core loss of Steel EMP33

III. IRON LOSSES MODEL

A. *Model description*

It is widely known that iron losses can be separated into two terms, eddy current and hysteresis losses, as in (1):

$$W_{fe} = Y(B_p)\,f + K(B_p)\,f^2 \qquad (1)$$

Dividing (1) by *f*, the formulation can be changed into a simple first-order polynomial with the following form.

$$\frac{W_{fe}}{f} = Y(B_p) + K(B_p)\,f \qquad (2)$$

In (2), $Y_{(Bp)}$ is the hysteresis loss coefficient and $K_{(Bp)}$ is the eddy current coefficient. Obviously, it is a simpler model since the coefficients K and Y depend only upon the flux density peak B_p,, which can be obtained from the measured special core losses through the least squares method.

B. *Characteristics of the model*

According to the above model description, only two coefficients need be determined, namely, Y and K, and they are all B_p dependent. This means it is not necessary to perform a complex mathematical procedure to obtain these coefficients.

C. *Loss Coefficients Determination*

The loss coefficients can be determined by the least-squares method using a first-order polynomial and as for the steel, the coefficients are given in Fig. 4. As seen in this figure, the linear characteristics are obvious.

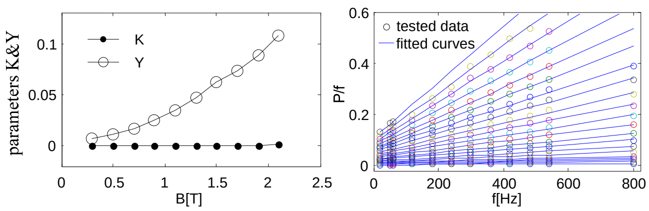

Fig. 4. Loss coefficients of steel EMP33

IV. COMPUTATION RESULT AND VALIDATION

Two different kinds of motors, namely, a high speed PM DC motor and a PM BLDC motor are used for validation. Details of these motors are given in Table II. Comparison of tested and computation iron losses of the two motors are given in Fig. 5 and Fig. 6.

TABLE II DETAILS OF THE MOTORS

Motor	1	2
Output(W)	400	250
Poles	2	4
Stator slots numbers	-	6
Rotor slots numbers	5	-
Stator outer diameter (mm)	47	75
Stator inner diameter (mm)	35.45	37
Core-length (mm)	30	10
Steel grade	EMP33	EMP24
Full processed	Yes	Yes

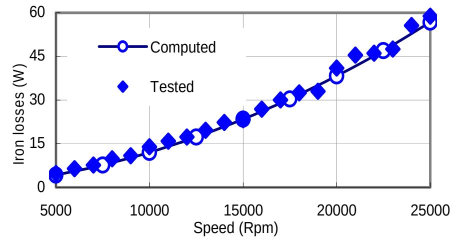

Fig. 5. Comparison of tested and computed iron losses on motor-1

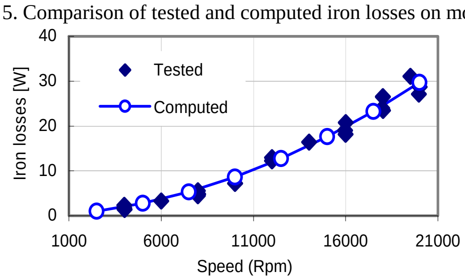

Fig. 6. Comparison of tested and computed iron losses on motor-2

V. CONCLUSIONS

A complete model for predicting iron losses, including material measurement, data fitting, FE computation and experimental validation, is proposed. The model is convenient to use and able to predict the iron losses of electric machines with good accuracy. The model's results and therefore its utility have been verified by comparison with test data.

VI. REFERENCES

[1] Giorgio Bertotti, "General properties of power losses in soft ferromagnetic material," *IEEE Trans. Magn.*, Vol.24, No.1, pp.621-630, 1988.

[2] Mircea Popescu, Dan.M. Ionel, "A Best-Fit Model of Power Losses in Cold Rolled-Motor Lamination Steel Operating in a Wide Range of Frequency and Magnetization," *IEEE Trans. Magn.*, Vol.43, No.4, pp.1753-7756, 2007.

[3] Jian Guo Zhu, Victor Stuart Ramsden, "Improved Formulations for Rotational Core Losses in Rotating Electrical Machines," *IEEE Trans. on Magn.*, vol.34, no.3, pp. 2234-2242, 1998.

[4] Lotten Tsakani Mthombeni, Pragasen Pillay, "Core Losses in Motor Laminations Exposed to High-Frequency or Nonsinusoidal Excitation," *IEEE Trans. Ind. Applicant.*, Vol.40, No.5, pp.1325-1332, 2004.

[5] Katsumi Yamazaki, Noriaki Fukushima, "Iron-Loss Modeling for Rotating Machines: Comparison Between Bertotti's Three-Term Expression and 3-D Eddy-Current Analysis," *IEEE Trans. on Magn.*, vol.46, no.8, pp. 3121-3124, 2010.

[6] MPG100D AC/DC Hysteresisgraph—User Manual, Brockhaus Messtechnik, Ludenscheid, Germany, 2002.