Simulation and Measurement of Iron Loss and Flux inside Silicon Steel Lamination under DC Biasing

Zhigang Zhao[1], Fugui Liu[1], Z.Cheng[2], *Senior Member, IEEE*, Youhua Wang[1], and Weili Yan[1]
[1] Province-Ministry Joint Key Laboratory of Electromagnetic Field and Electrical Apparatus Reliability, Hebei University of Technology, Tianjin 300130, CHINA
[2] R & D Center, Baoding Tianwei Group Co., LTD, Tianwei West Road 2399, Baoding 071056, CHINA
iamsam@hebut.edu.cn

Abstract —A laminated core model (LCM) of product level was proposed and prototyped for investigating the electromagnetic behavior of silicon steel sheets under DC biasing. The magnetic properties of laminated core under DC biasing working condition have been examined in detail, such as the B_m-H_b and B_m-W_t curves. The comparison between the property data provided by the manufacturer and the measured data obtained by the authors was done. The effect of the material magnetic property under different DC-biased magnetization on iron loss and flux distribution in lamination configuration was investigated in detail. Some practical approaches to nonlinear and anisotropic eddy current problems under DC-biased excitation conditions are proposed. The numerical modeling results have been verified by the measured loss and flux data, the good agreement between them indicates that the proposed engineering-oriented method is effective in solving the dc biasing eddy current problem.

I. INTRODUCTION

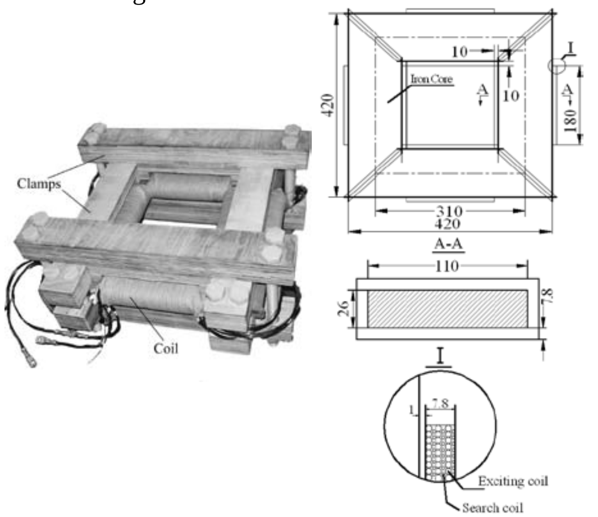
With the development of High Voltage Direct Current Transmission (HVDC), power transformers working near a HVDC system are often affected by the DC biasing. The influence of DC biasing magnetization on operating AC power transformers has been paid much attention.

Meanwhile, the increasing importance of the magnetic property modeling of electrical steels has been commonly recognized in electromagnetic field computation [1]. The silicon steel lamination under DC-biased magnetization will experience a distorted and asymmetrical hysteretic loop and the iron loss is also increased compared to those under sinusoidal excitations [2]. Unfortunately, the available material property data are often insufficient and that cuts down the effectiveness of the dc-biased electromagnetic design. The material model is usually based on measurement performed using certain standard procedures and under certain external environmental conditions, which are, in general, different from those present under working conditions, especially under DC biasing magnetization. And we do not clearly know the distinctiveness between the magnetic property of the real laminated core under DC-biased condition and that obtained by the standard Epstein frame or Single Sheet Tester (SST). It is certainly important to validate the usefulness and effectiveness of property data when the laminated iron core is working under DC Biasing.

In this paper, the experimental study on the magnetic property of the oriented silicon steel sheets under DC bias is performed and the material model of the DC-biased transformer is established for field analysis. An engineering oriented simulation method is proposed to analyze the 3-D nonlinear and anisotropic eddy current problems with AC voltage and DC current supply constraint at the same time.

II. DATA OF MODEL

The detailed structural dimension of the model is shown in Fig.1 and Table I.



(a) Photo of laminated core model (b) Structural dimensions
Fig.1. Laminated core model

TABLE I
PARAMETERS OF CORE AND COILS

Parameters	LCM	Remarks
Number of turns of exciting coil	108/212/312	The turns of coils can be changed
Number of turns of search coil	108/212/312	
Mean length of magnetic path(m)	1.24	
Length of silicon sheet (mm)	420	
Width of silicon sheet (mm)	110	
Thickness of core-leg (mm)	25	
Net area of cross section of core(mm^2)	2667.5	Packing factor: 0.97
Total weight of iron core (kg)	26.3	
Cross-section area of joints (mm^2)	4.01×10^3	

III. MAGNETIC PROPERTY UNDER DC BIASING

The experimental scheme based on the LCM is designed, in which the LCM is driven by both AC and DC currents simultaneously as shown in Fig.2.

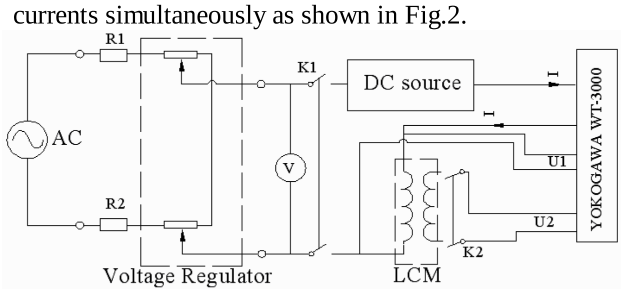


Fig.2. Experiment scheme of DC-biased magnetization

The comparison between measured magnetic property data under DC-biased condition and the curves under standard condition that provided by WSPC (Wuhan Steel Processing Co., Ltd) are shown in Fig.3 and Fig.4.

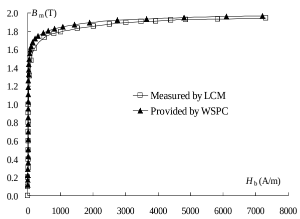


Fig.3. *B*-*H* curve

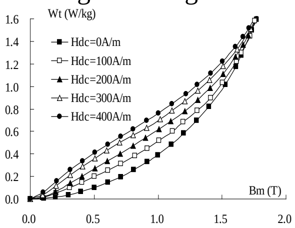


Fig.4. B_m-W_t curves

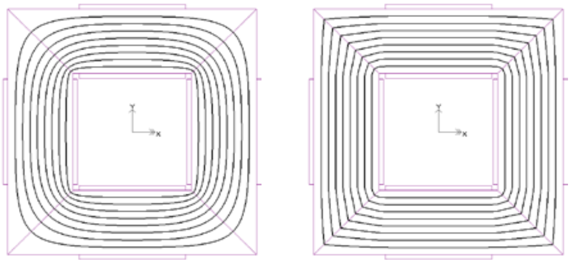
IV. SIMULATION AND VERIFICATION

The effects of the different DC-biased magnetic field strength H_{dc} on the iron loss and flux inside the laminated sheets have been examined based on LCM. The exciting mode of the LCM is listed in Table II.

TABLE II
DIFFERENT EXCITATION CONDITIONS

H_{dc}(A/m)			
100		400	
Cases	B_m(T)	Cases	B_m(T)
1	0.5	6	0.5
2	1.0	7	1.0
3	1.4	8	1.4
4	1.7	9	1.7
5	1.8	10	1.8

Take Case 3 for example, 2-D magnetic field distribution in the LCM was examined, as shown in Fig.5.



(a) Isotropic permeability (b) Anisotropic permeability

Fig.5. 2-D magnetic filed distribution

A. Finite Element Model

The simplified finite element model of the laminated grain-oriented silicon steel sheets as shown in Fig.6 has the following characteristics.

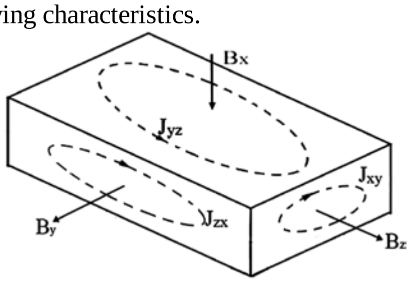


Fig.6. 3-D eddy current simulation model of core limb

1) Treatment of magnetic anisotropy

The applied field to LCM is almost along the rolling direction, making it is a weak magnetic anisotropy problem, and the orthogonal anisotropic permeability is assigned in all the laminations.

2) Homogenization of electric isotropy

The current density produced by transverse flux inside the laminations is negligible, since the flux in the rolling direction is much greater than in the transverse direction, see Fig.5 (b).Consequently, the electric conductivity (σ) is modeled as isotropic by simply assuming its value zero or very low [3-7].

B. Modeling of Iron Loss

The measured and calculated results of total iron loss of DC-biased LCM are shown in Table III. The obtained specific B_m-W_t curves corresponding to different applied DC magnetic field strength are used in field computation.

TABLE III
TOTAL IRON LOSS UNDER DIFFERENT EXCITING CASES

Iron loss（W）					
Case	Measured	Calculated	Case	Measured	Calculated
1	6.98	6.41	6	10.61	9.72
2	16.10	15.03	7	19.87	18.94
3	25.74	24.16	8	29.03	28.27
4	37.84	35.94	9	39.54	37.85
5	45.11	43.35	10	45.99	44.61

C. Modeling of Flux inside Lamination

The measured and calculated results of the average flux inside iron core under different exciting conditions have been obtained, as shown in Table V.

TABLE V
MEASURED AND CALCULATED AVERAGE FLUX

Flux inside iron core(mWb)					
Case	Measured	Calculated	Case	Measured	Calculated
1	4.706	4.738	6	5.200	5.234
2	4.891	4.903	7	5.302	5.337
3	4.957	4.971	8	5.375	5.392
4	5.051	5.082	9	5.409	5.418
5	5.144	5.179	10	5.425	5.431

V. CONCLUSION AND DISCUSSION

The DC-biased magnetic property is obtained based on the LCM and compared with the “standard” data. An engineering-oriented simulation model for DC biasing field computation is presented. The calculated and measured results of total iron loss and flux for different excitation conditions are practically in good agreement.

ACKNOWLEDGMENT

This work was supported in part by the National Natural Science Foundation of China under grant no. 50777042, and the Natural Science Foundation of Hebei Province, China, under grant E2006001036.

VI. REFERENCES

[1] A.J.Moses. Characterisation and performance of electrical steels for power transformers operating under extremes of magnetisation conditions. Presented at International Colloquium Transformer Research and Asset Management, Cavtat, Croatia, Nov.12-14, 2009.

[2] D. Miyagi, T. Yoshida, M. Nakano, et al. Development of measuring equipment of dc-biased magnetic properties using open-type single-sheet tester. *IEEE Trans. Magn.*, 2006, 42(10):2846-2848.

[3] H.Kaimori, A.Kameari, K.Fujiwara. FEM computation of magnetic field and iron loss in laminated iron core using homogenization method. *IEEE Trans. on Magn.*, 2007, 43(4):1405-1408.

[4] K.Preis, O.Biro, I.Ticar. FEM analysis of eddy current losses in nonlinear laminated iron cores. *IEEE Trans. on Magn.*, 2005, 41(5):1412-1415.

[5] H.Igarashi, K.Watanabe, A.Kost. A reduced model for finite element analysis of steel laminations. *IEEE Trans. on Magn.*, 2006, 42(4):739-742.

[6] M.Enokizono, H.Shimoji, A.Ikariga, et al. Vector magnetic characteristics analysis of electrical machines. *IEEE Trans. on Magn.*, 2005, 41(5):2032-2035.

[7] Z.Cheng, N.Takahashi, B.Forghani, et al. Analysis and measurements of iron loss and flux inside silicon steel laminations. *IEEE Trans. on Magn.*, 2009, 45(3):1222-1225.