Measurement and Modelling of Magnetic Properties of Fe-based Amorphous Magnetic Material

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I, Pejush Chandra Sarker declare that this thesis, is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the School of Electrical and Data Engineering at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

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The following articles based on this thesis were published during the study.

Peer reviewed international journal publications:

[1] **P. C. Sarker**, M. R. Islam, Y. Guo, J. G. Zhu, and H. Y. Lu, "State-of-the-art technologies for development of high frequency transformers with advanced magnetic materials," *IEEE Transactions on Applied Superconductivity*, vol. 29, no. 2, Mar. 2019, Art. no. 7000111. (DOI: 10.1109/TASC.2018.2882411)

[2] **P. C. Sarker**, Y. Guo, H. Y. Lu, and J. G. Zhu, "A generalized inverse Preisach dynamic hysteresis model of Fe-based amorphous magnetic materials," *Journal of Magnetism and Magnetic Material*, vol. 514, Nov. 2020, Art. no. 167290. (https://doi.org/10.1016/j.jmmm.2020.167290)

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[4] **P. C. Sarker**, Y. Guo, H. Y. Lu, and J. G. Zhu, "Improvement on parameter identification of modified Jiles-Atherton model for iron loss calculation," *Journal of Magnetism and Magnetic Materials*, vol. 542, Jan. 2022, Art. no. 168602. (https://doi.org/10.1016/j.jmmm.2021.168602)

Abstract

Fe-based amorphous magnetic materials are attracting more and more attentions in the low and medium frequency electrical machines and transformers due to their favourable properties of low core loss and high saturation magnetic flux density. In this study, the core loss of a Fe-based amorphous magnetic material (amorphous 1k101) is measured and modelled under alternating and rotating magnetic field excitations. In particular, for numerical analysis using the vector magnetic potential under alternating magnetic field, an inverse magnetic hysteresis model is needed to predict the magnetic field strength from the magnetic flux density. This study proposes a generalised inverse Preisach model for characterisation of the magnetic material which considers the reversible magnetisation and magnetisation dependent hysteresis effect. Thus, the proposed inverse Preisach model improves the accuracy of the prediction of core loss compared to the normal inverse Preisach model. In addition, a modified Jiles-Atherton (J-A) model is utilised for modelling the magnetic material which eliminates the drawbacks of the inverse Preisach model such as high computational time and memory requirements. The implementation of J-A model is associated with model parameter identification which is generally carried out by different optimisation techniques. In the optimisation techniques, an additional error criterion along with conventional error criterion for the identification of the J-A model parameters is proposed in this study which improves the core loss prediction**.** Furthermore, a modified J-A model is proposed to improve the agreement between experimental and calculated results especially at the low magnetic induction levels by introducing a scaling factor in the anhysteretic magnetisation. Both the proposed inverse Preisach model and modified J-A model are verified by the results obtained from experimental methods and existing modellings in the literature. Moreover, the rotating (two-dimensional) magnetic properties of the Fe-based amorphous magnetic material is experimentally investigated in this thesis where a square specimen tester is exploited for experimental measurement. For modelling of the rotational hysteresis loss, an improved and simplified analogical model is proposed and verified for the magnetic material. The total specific rotational loss of the amorphous magnetic material for both circular and elliptical rotating magnetic fields are measured and modelled. Furthermore, an optimal design of a high-power density medium frequency transformer (MFT) using the Fe-based amorphous magnetic material is presented in this thesis where the effects of magnetisation current is considered in the design process. A prototype of the MFT is utilised for the experimental verification of the design.

Keywords: Fe-based amorphous magnetic material; Direct and inverse Preisach models; Jiles-Atherton model; Hysteresis loss; Dynamic core loss; Alternating core loss; Rotational core loss; Medium frequency transformer.

Content

CERTIFICATE OF ORIGINAL AUTHORSHIP i
ACKNOWLEDGMENTS ii
LIST OF PUBLICATIONS iii
ABSTRACT iv
LIST OF FIGURES xi
LIST OF TABLES xv
ABBREVIATIONS xvi
NOMENCLATURE xvii
Chapter 1 Introduction 1
1.1 Background of the Research 1
1.2 Research Gaps 4
1.3 Research Objectives 6
1.4 Contributions of the Research 7
1.5 Thesis Outline 8
References 9
Chapter 2 Literature Review 14
2.1 Magnetisation Process 14
2.2 Measurement and Modelling of Alternating Core Loss 17
2.2.1 Measurement of Alternating Core Loss 17
2.2.1.1 Thermal or Calorimeter Technique 17
2.2.1.2 Electrical Technique 18
2.2.2 Modelling of Alternating (1-D) Core Loss 21
2.2.2.1 Empirical Core Loss Model 21
2.2.2.2 Microstructures of the Material-Based Models 23
2.2.2.2.1 Preisach Model 24
2.2.2.2.2 J-A Model 25
2.3 Measurement of 2-D Core Loss 29
2.3.1 Calculation of **H** Components 32
2.3.2 Calculation of **B** Components 34
2.3.3 Apparatuses of 2-D Measurement System 35
2.4 Design of the MFT 37
2.4.1 Winding AC Resistance Modelling 38
2.4.2 Leakage Inductance Modelling 41

2.4.3 Temperature Rise 42

2.5 Conclusion 43

References 43

Chapter 3 Modelling of Amorphous Magnetic Material Using Empirical and Preisach Models 49

3.1 Introduction 49

3.2 Empirical Model 52

3.3 Preisach Model 53

3.3.1 Normal Preisach Model 53

3.3.2 Generalised Preisach Model 54

3.4 Inverse Preisach Model 55

3.4.1 Normal Inverse Preisach Model 55

3.4.2 Proposed Inverse Preisach Model 57

3.5 Implementation of Preisach Models 58

3.5.1 Implementation of Normal Preisach Model 59

3.5.2 Implementation of Generalised Preisach Model 60

3.5.2.1 Identification of Anhysteretic Magnetisation Curve 60

3.5.2.2 Identification of Squareness 63

3.5.2.3 Identification of Feedback Coefficient 63

3.6 Implementation of Inverse Preisach Models 67

3.6.1 Implementation of the Normal Inverse Preisach Model 67

3.6.2 Implementation of Generalised Inverse Preisach Model 68

3.7 Dynamic Hysteresis Effects 71

3.7.1 Identification of Dynamic Coefficients 72

3.7.2 Incorporation of Dynamic Hysteresis with Inverse Preisach Model 74

3.8 Experimental Verification 74

3.8.1 Experimental Testing Method 74

3.8.2 Verification of Simulated Results 77

3.9 Conclusion 83

References 84

Chapter 4 Modelling of Amorphous Magnetic Material Using Jiles-Atherton Model 87

4.1 Introduction 87

4.2 Jiles-Atherton model 89

4.2.1 Formulation 90

4.2.2 Identification of Model Parameters 91

4.3 Proposed Model 92
4.4 Inverse J-A model 98
4.5 Inclusion of Dynamic Losses 99
4.6 Results and Discussions 100
4.7 Conclusion 106
References 106
Chapter 5 Measurement and Modelling of Core Loss Under Rotating Magnetic Field 109
5.1 Introduction 109
5.2 2-D Core Loss Testing System 111
5.2.1 2-D Core Loss Tester 111
5.2.2 Measurement Methods for **B** and **H** 112
5.2.3 Misalignment of **H** Sensing Coils 115
5.2.4 Feedback System 116
5.3 Core Loss Measurements under Different Rotating Magnetic Fields 117
5.3.1 Core Loss Measurement under Circularly Rotating Magnetic Field 117
5.3.2 Core Loss under Alternating Magnetic Field 119
5.3.3 Core Loss under Elliptical Magnetic Field 122
5.4 Modelling of Circularly Rotational Losses 123
5.4.1 Rotational Hysteresis Model 123
5.4.1.1 Existing Rotational Hysteresis Models 123
5.4.1.2 Proposed Rotational Hysteresis Model 125
5.4.2 Modelling of Rotational Eddy Current Loss 126
5.4.3 Modelling of Rotational Excess Loss 127
5.5 Modelling of Alternating Core Loss 129
5.6 Modelling of Elliptical Core Loss 130
5.7 Experimental Verification of Modelling of Core Losses 130
5.8 Conclusion 132
References 133
Chapter 6 Design of Medium Frequency Transformer 135
6.1 Introduction 135
6.2 Modelling of MFT 136
6.2.1 Core Loss 137
6.2.2 Core Geometry 138
6.2.3 Insulation Design 140

6.2.4 Winding Wire Selection 140
6.2.5 Consideration of Transformer’s No-Load Current 141
6.2.6 Winding Losses 142
6.2.7 Leakage Inductance 143
6.2.8 Temperature Rise 144
6.3 Design Methodology 145
6.4 Experimental Testing 148
6.5 Conclusion 150
Reference 151
Chapter 7 Conclusion and Future Works 153
7.1 Conclusion 153
7.2 Possible Future Works 154

List of figures

Figure No.	Figure Caption	Page
Fig. 1.1	A typical MFT based voltage conversion system	1
Fig. 2.1	The general pattern of B-H loop of a magnetic material.	15
Fig. 2.2	A typical initial B-H curve of a magnetic material	15
Fig. 2.3	Orientation change of magnetic moments at magnetic domain wall	16
Fig. 2.4	The block diagram of core loss measurement system using calorimeter	18
Fig. 2.5	Schematic diagram of core loss measurement using oscilloscope	19
Fig. 2.6	Schematic diagram of core loss measurement with DC bias	20
Fig. 2.7	Core loss measurement using capacitive cancellation	21
Fig. 2.8	(a) Rectangular hysteresis model of magnetic dipoles and (b) Preisach diagram	24
Fig. 2.9	The typical pattern of the rotational hysteresis loss of a magnetic material	30
Fig. 2.10	The typical pattern of the alternating hysteresis loss of a magnetic material	30
Fig. 2.11	Induced torque angle due to the rotational magnetic field at general magnetic flux density	31
Fig. 2.12	Induced torque angle due to the rotational magnetic field at saturation magnetic flux density	31
Fig. 2.13	(a) **H** coil in one dimensional configuration and (b) **H** coils in two-dimensional configuration	32
Fig. 2.14	The arrangement of two coil method for measurement of **H** components	33
Fig. 2.15	A typical Hall element which uses the Hall effect	33
Fig. 2.16	Searching coil arrangement for (a) uniform **B**, and (b) nonuniform **B**	34
Fig. 2.17	Measurement of **B** component using B tips	35
Fig. 2.18	Block diagram of a square specimen tester	36
Fig. 2.19	Large sheet sample-based tester for rotational core loss measurement	37
Fig. 2.20	Typical pattern of R_{ac} for different layers (p) with frequency.	38
Fig. 2.21	Conversion of solid conductor from round shape to rectangular shape	38
Fig. 2.22	Conversion method of a Litz wire to several layers for calculation of AC resistance	40
Fig. 2.23	Typical leakage inductance with frequency for turn ratios (m) 1 and 2.	41
Fig. 3.1	(a) Rectangular hysteresis model of magnetic dipoles [3.23], [3.25], and (b) Preisach diagram	53
Fig. 3.2	Limiting loop of the Fe-based amorphous magnetic material	59
Fig. 3.3	Applied magnetic field strength and corresponding measured and calculated magnetic flux densities	59

Fig. 3.4 Excitation magnetic field strength for prediction of anhysteretic magnetisation using normal Preisach model: (a) upper value of anhysteretic magnetisation, and (b) lower value of anhysteretic magnetisation 61

Fig. 3.5 Magnetisation processes for anhysteretic magnetisation using normal Preisach model: (a) upper value of anhysteretic magnetisation, and (b) lower value of anhysteretic magnetisation 62

Fig. 3.6 Anhysteretic magnetisation curve of the Fe-based amorphous magnetic material calculated by the normal Preisach model and its derivative with respect to magnetic field strength H 62

Fig. 3.7 Feedback coefficient for the upward magnetisation of the Fe-based amorphous magnetic material at different magnetic flux density magnitudes 63

Fig. 3.8 Comparison of the B-H loops predicted by using constant feedback coefficient, proposed feedback coefficient, and no-feedback coefficient with the experimental result 65

Fig. 3.9 The feedback coefficient of upward magnetisation with the change of B_m for $H \geq H_c$. 65

Fig. 3.10 The feedback coefficient of upward magnetisation with the change of H_m for $H \geq H_c$ 66

Fig. 3.11 Calculated and measured magnetic field strengths and magnetic flux densities for minor loops 67

Fig. 3.12 Flow chart of the proposed inverse Preisach model 69

Fig. 3.13 Variable squarenesses for inverse and direct Preisach model with: (a) maximum magnetic flux density, and (b) maximum magnetic field strength, respectively 71

Fig. 3.14 Curve fitting of the measured core loss data with frequency for different maximum magnetic flux densities, (a) 1.08 T, and (b) 1.41 T 73

Fig. 3.15 Block diagram of the experimental set up for measuring B-H loops of magnetic materials 75

Fig. 3.16 Comparison among measured and calculated B-H loops for minor loops over a major loop 76

Fig. 3.17 Comparison between measured and calculated power losses per cycle at 1.08 T. 77

Fig. 3.18 Comparison of calculated and measured hysteresis loss using inverse Preisach models with different squareness conditions 80

Fig. 3.19 A comparison between calculated and measured core losses versus frequency at B_m=1.29 T with two different loss units: (a) W/m^3/Hz and (b) W/kg/Hz 82

Fig. 3.20 A comparison of errors in calculation of core loss using different models 82

Fig. 3.21 Calculated and measured B-H loops at 500 Hz and 1.29 T 83

Fig. 4.1 Comparison of B-H loops obtained from measured and J-A models for 1 Hz sinusoidal excitations at (a) B_m = 1.26 T and (b) B_m = 0.83 T 94

Fig. 4.2 The percentage of error in the calculation of coercive magnetic field strength, ε_{Hc} with the change of peak magnetic flux densities. 94

Fig. 4.3 Flow chart of the proposed method for the identifying the J-A model parameters. 96

Fig. 4.4 Pareto-optimal solutions by optimisation technique to identify model parameters at 1.26 T. 97

Fig. 4.5 The values of the loss factor k with the change of peak magnetic field strength, H_m 97

Fig. 4.6 The values of scaling factor v with the change of peak magnetic field strength, H_m 98

Fig. 4.7 The values of the loss factor k with the change of peak magnetic flux density, B_m 99

Fig. 4.8 The values of scaling factor v with the change of peak magnetic flux density, B_m 99

Fig. 4.9 Percentage of core loss error, ε_r with change of peak magnetic flux densities for the proposed error criterion and existing error criterion 101

Fig. 4.10 Percentage of root mean square errors of the calculation of B at different peak magnetic flux densities at different conditions of J-A models 101

Fig. 4.11 Comparison between calculated and measured H at B_m=1.38 T and 1 Hz excitation 102

Fig. 4.12 Comparison between the calculated and measured B-H loops for two minor loops on a major loop. 103

Fig. 4.13 Core loss separation using the proposed modified inverse J-A model. 103

Fig. 4.14 Comparison between the measured and calculated B-H loops at 1.41 T and 0.67 T for 500 Hz excitations 104

Fig. 4.15 Comparison between the measured and calculated core loss at 500 Hz with different peak magnetic flux densities 105

Fig. 4.16 Comparison among different core loss models at (a) B_m=1.08 T and (b) B_m=1.29 T. 106

Fig. 5.1 Block diagram of 2-D square specimen testing system 111

Fig. 5.2 A photo of the 2-D core loss measurement set-up 112

Fig. 5.3 Calibration of **H** sensing coils using a solenoid 114

Fig. 5.4 Rotation of the co-ordinate axis to deal the misalignment problems 116

Fig. 5.5 Feedback system used for the 2-D magnetic properties measurement system 117

Fig. 5.6 Rotational core losses of the amorphous magnetic material with B_m for different frequencies 118

Fig. 5.7 Loci of **B** at different magnetic flux densities under 50 Hz rotating magnetic field 119

Fig. 5.8 Loci of **H** at different magnetic flux densities under 50 Hz rotating magnetic field 119

Fig. 5.9 B-H loops under alternating magnetic field at 50 Hz and peak value of magnetic flux density 1.40 T on X and Y-axes 120

Fig. 5.10 Alternating core losses of the amorphous magnetic material with B_m for different frequencies 120

Fig. 5.11 The alternating core losses of the amorphous material with B_m under 50 Hz sinusoidal excitation 121

Fig. 5.12 The rotational core loss of the amorphous material with B_m under 50 Hz rotating magnetic field 121

Fig. 5.13 Elliptical loci of **B** at 50 Hz when major axis is on (a) X-axis and (b) Y-axis, and the corresponding loci of **H** when major axis is on (c) X-axis and (d) Y-axis 122

Fig. 5.14 Total core loss with different axis ratios at 50 Hz excitation 123

Fig. 5.15 Modification parameter a_m of the alternating hysteresis loss-based model rotational hysteresis loss model 125

Fig. 5.16 Curve fitting of the measured core loss data with frequency for different maximum magnetic flux densities, e.g., (a) 0.15 T, (b) 0.50 T, (c) 1.00 T and (d) 1.40 T 128

Fig. 5.17 Rotating and alternating excess loss coefficients with magnetic flux density 128

Fig. 5.18 Comparison of different models for modelling rotational hysteresis loss of the amorphous magnetic material 129

Fig. 6.1 A design sketch of a double C-core type MFT (only inside conductors are shown) 138

Fig. 6.2 *B-H* curve of the selected AMCC 50 core 141

Fig. 6.3 Conversion method of a Litz wire to several layers for calculation of AC resistance 142

Fig. 6.4 Conversion method of a Litz wire-based transformer windings to several layers for calculation of leakage inductance 143

Fig. 6.5 The flow chart of the optimal design of MFT 146

Fig. 6.6 Efficiency with respect to power density with inclusion and exclusion of the no-load current 147

Fig. 6.7 The experimental circuit for testing the MFT 149

Fig. 6.8 A photo of experimental set-up for testing the MFT 149

Fig. 6.9 Measured primary and secondary voltages, and excitation current of the MFT at no-load condition. 150

Fig. 6.10 The measured magnetic flux density of the MFT. 150

List of Tables

Table No.	Table Caption	Page
Table 3.1	Different parameters of the tested core	75
Table 3.2	(a) Comparison of calculated and measured hysteresis loss (W/m^3/Hz) for Preisach models (b) Comparison of calculated and measured hysteresis loss (W/kg/Hz) for Preisach models	78
Table 3.3	(a) Comparison of calculated and measured hysteresis loss (W/m^3/Hz) for inverse Preisach models (b) Comparison of calculated and measured hysteresis loss (W/kg/Hz) for inverse Preisach models	79
Table 3.4	Comparison of calculated and measured hysteresis loss with minor loops	81
Table 5.1	Calibration of H_x sensing coil	115
Table 5.2	Calibration of H_y sensing coil	115
Table 6.1	Comparison of winding loss and leakage inductance from primary side of a selected design of MFT (2.5 kW, 200V/400V)	147
Table 6.2	Selected optimal design parameters of MFT (2.5 kW, 1 kHz, 200V/400V)	148

Abbreviations

MFT	Medium frequency transformer
HFT	High frequency transformer
1-D	One-dimensional
J-A	Jiles-Atherton
DC	Direct current
AC	Alternating current
SST	Solid state transformer
GSE	Generalized Steinmetz equation
SiFe	Silicon iron
NiFe	Nickel iron
CoFe	Cobalt iron
SMC	Soft magnetic composite
2-D	Two-dimensional
Fe	Iron
Co	Cobalt
Ni	Nickel
OSE	Original Steinmetz equation
IGSE	Improved generalised Steinmetz equation
UTS	University of Technology Sydney
CUT	Core under test
FEM	Finite-element method
DSP	Digital signal processing
GRG	General reduced gradient
NSE	Natural Steinmetz equation
AWG	American wire gauge
3-D	Three-dimensional
RMS	Root mean square
WCSE	Waveform coefficient Steinmetz equation

Nomenclature*

P	Core loss
t	Time
B	Magnetic flux density
$\mathbf{B}$	Magnetic flux density vector
K_h, K_e, K_{exc}, a, b, and c	Constants associated with core loss separation model
k, α and β	Steinmetz parameters
f_r	Fundamental frequency
f_{eq}	Equivalent frequency associated with OSE model
k_i	Parameter associated with GSE model
f	Frequency
T	Time period
ΔB	Magnetic flux density variation
k_N	Parameter associated with NSE model
K_{FWC}	The ratio of areas of the non-sinusoidal and sinusoidal waveforms
V	Flow rate of the coolant
C_s	Specific heat of fluid
A	Cross section of coolant path
B_m	Maximum magnetic flux density
i_p	Primary current
v_s	Secondary voltage
H	Magnetic field strength
$\mathbf{H}$	Magnetic field strength vector
R_{ref}	Resistance of current sensor
v_R	Voltage across the current sensor resistor
C_r	Resonant capacitance
η	Porosity factor
d_t	Conductor height
M_w	$\alpha_1 d_t \coth\left(\alpha_1 d_t\right)$
D_w	$2\alpha_1 d_t \tanh\left(\dfrac{\alpha_1 d_t}{2}\right)$
M_w'' and D_w''	Imaginary parts of M_w and D_w respectively
M_w' and D_w'	Real parts of M_w and D_w respectively

* Symbols that are not listed are explained where they firstly appear

α_1	$\sqrt{\frac{j\omega\eta\mu_0}{\rho_r}}$
ω	Angular frequency
μ	Permeability
R_{dc}	DC resistance of the winding
R_{ac}	AC resistance of the winding
Δ	Ratio of thickness of conductor and skin depth
δ	Skin depth
γ	$d_c/(\sqrt{2}\delta)$
d_c	Diameter of conductor
I_{rms}	Root mean square value of current
I'_{rms}	Derivative of I_{rms}
N_s, N_{s1}, N_{s2}	Number of strands, and numbers of strands of primary and secondary windings
d_s	Diameter of a strand.
Δ_s	Ratio of thickness of conductor and skin depth for Litz wire
G_W	Core window width
H_w	Core window height
M	Magnetisation
$\mathbf{M}$	Magnetisation vector
M_{irr}	Irreversible magnetisation
M_{rev}	Reversible magnetisation
H_e	Effective magnetic field strength
M_s	Saturated magnetisation
B_e	Effective magnetic flux density
H_x, H_y	Magnetic field strength components in X and Y-directions
H_n	Magnetic field strength at the last reversal point
L_{lP}	Leakage inductance refer to primary winding
χ	Magnetic susceptibility
χ_{io}	Initial susceptibilities of normal magnetisation
χ_{anho}	Initial susceptibilities of anhysteretic magnetisation
ΔT	Temperature rise
R_{th}	Thermal resistance
I_0	No-load transformer current
B_x, B_y	Magnetic flux density components in-X and Y-directions
A_c	Cross sectional area of the core

K_f	Form factor
R_{ac1} and R_{ac2}	AC resistances of primary and secondary windings
V_p, V_s, I_s, I_p	Voltage and current of primary and secondary windings
d_{ins}, d_{iso}	Thicknesses of insulation and isolation
d_{w1}	Diameter of the primary Litz wire
d_{w2}	Diameter of the secondary Litz wire
W_1	Primary half winding width
W_2	Secondary half winding width
M_{an}	Anhysteretic magnetisation
H_e	Effective magnetic field strength
σ	Conductivity of the amorphous ribbon
d_l	Thickness of amorphous ribbon
A_l	Cross sectional area of the lamination
G, V_0	Constant coefficients depending on material metallurgical properties