



Equivalent Circuit Models of the Permanent Magnet Synchronous Motor with Predictable Core Loss

by Xin Ba

Thesis submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy

under the supervision of Professor Youguang Guo and Professor Jianguo Zhu

University of Technology Sydney
Faculty of Engineering and Information Technology
School of Electrical and Data Engineering
May 2022

Title of the thesis:

Equivalent Circuit Models of the Permanent Magnet Synchronous Motor with Predictable Core Loss

Ph.D. candidate:

Xin Ba

Email: Xin.BA@student.uts.edu.au

Principal Supervisor:

Professor Youguang Guo

Email: youguang.guo-1@uts.edu.au

Co-Supervisor:

Professor Jianguo Zhu

Emails: jianguo.zhu@sydney.edu.au, jianguo.zhu@uts.edu.au

Address:

School of Electrical and Data Engineering

Faculty of Engineering and Information Technology

University of Technology Sydney, 15 Broadway, Ultimo, NSW 2007, Australia

CERTIFICATE OF ORIGINAL AUTHORSHIP

I, Xin Ba 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.

This research is supported by the Australian Government Research Training Program.

Signature: Production Note:
Signature removed prior to publication.

Date: November 2022

ACKNOWLEDGMENT

First and foremost, I would like to express special appreciate and heart felt thanks to my supervisors, Professor Youguang Guo, Jianguo Zhu and Chengning Zhang, for the continuous support in my research. Their mentorship, guidance and sincere encouragement were invaluable throughout the Ph.D. study.

The gratitude also goes to staff of the school, Mr. Russell Nicholson, Mr. Brett Lowder, Dr. Mike Zhong, A/Prof. Peter Watterson and Dr. Zhenjie Gong for their technical support and my fellow group-mates for the invaluable suggestions.

I would like to acknowledge University of Technology Sydney, Chinese Scholarship Council and Beijing Institute of Technology for the financial assistance to my research.

Finally, I appreciate my family for their cooperations, inspirations and supports during the entire course of my Ph.D.

LIST OF PUBLICATIONS

The following articles were published during the thesis work.

Peer reviewed international journal publications:

- [1] **X. Ba**, Y. Guo, J. Zhu, and C. Zhang, "An equivalent circuit model for predicting the core loss in a claw-pole permanent magnet motor with soft magnetic composite core," *IEEE Trans. Magn.*, vol. 54, no. 11, article 8105506, 2018.
- [2] **X. Ba**, P. Wang, C. Zhang, J. G. Zhu, and Y. Guo, "Improved deadbeat predictive current control to enhance the performance of the drive system of permanent magnet synchronous motors," *IEEE Tran. Appl. Supercond.*, vol. 31, no. 8, pp. 1-4, article 0603004, Nov. 2021.
- [3] **X. Ba**, Z. Gong, Y. Guo, C. Zhang, and J. Zhu, "Development of equivalent circuit models of permanent magnet synchronous motors considering core loss," *Energies*, vol. 15, no. 6, p. 1995, Mar. 2022.
- [4] Z. Gong, C. Zhang, **X. Ba** and Y. Guo, "Improved deadbeat predictive current control of permanent magnet synchronous motor using a novel stator current and disturbance observer," *IEEE Access*, vol. 9, pp. 142815-142826, 2021.
- [5] Z. Gong, **X. Ba**, C. Zhang, and Y. Guo, "Robust sliding mode control of the permanent magnet synchronous motor with an improved power reaching law," *Energies*, vol. 15, no. 5, p. 1935, Mar. 2022.
- [6] **X. Ba**, Z. Gong, Y. Guo, C. Zhang, and J. Zhu, "A generalized per-phase equivalent circuit model of the PMSM considering the core loss and magnetic saturation effect," submitted to *IEEE Trans. Transportation Electrification*.
- [7] L. Liu, **X. Ba**, Y. Guo, G. Lei, X. Sun, and J. Zhu, "Improved iron loss prediction models for interior PMSMs considering coupling effects of multiphysics factors," submitted to *IEEE Trans. Transportation Electrification*.

ABSTRACT

The core loss modeling in the equivalent circuit and developing regulation methods of the core loss are among the key technologies to analyze the performance and improve the efficiency of the permanent magnet synchronous motor (PMSM). Nowadays, understanding, modeling, and regulating the core loss of the PMSM play increasing crucial roles when developing high-speed, high-efficiency, high-torque density and high-power density motors. Therefore, this thesis aims to develop generalized equivalent circuit models (ECMs) of the PMSM with the predictable core loss, including per-phase ECM and d - and q -axis ECMs. Firstly, the core loss with the 3-dimensional rotating magnetic field is investigated, and the method of how to model the core loss into the ECM is developed, in which the equivalent core loss resistance is modelled as a function of the motor speed to achieve high accuracy over the entire speed operating range, and then an attempt of adopting the proposed ECM in deadbeat predictive current control to improve the dynamic response and robustness of the PMSM drive system is made. Secondly, to further increase the core loss prediction accuracy especially in load conditions, a novel generalized per-phase ECM of the PMSM with predictable core loss is proposed. Experimental tests of the PMSM prototype suggest that the prediction precision of both the core loss and the output electromagnetic characteristic is effectively enhanced over the entire speed and torque operating range. Finally, novel generalized d - and q -axis ECMs of the PMSM with predictable core loss are established to benefit motor control and enable the core loss management. Moreover, to make the most use of the stator current and decrease the electromagnetic loss of the PMSM, an improved maximum torque per ampere current control considering both the core loss and copper loss is carried out theoretically. The research results of this thesis will improve the accuracy of the ECMs and mathematical models of the PMSM, and hence provide theoretical and technical support for the improvement of the optimization methods and control strategies of the PMSM.

Keyword: Equivalent circuit model, core loss, permanent magnet synchronous motor, motor control.

Content

CERTIFICATE OF ORIGINAL AUTHORSHIP	i
ACKNOWLEDGMENT	ii
LIST OF PUBLICATIONS.....	iii
ABSTRACT	iv
LIST OF FIGURES	vii
LIST OF TABLES	xi
ABBREVIATIONS	xii
LIST OF SYMBOLS	xiv
CHAPTER 1. INTRODUCTION	1
1.1 Background of the Research.....	1
1.2 Research Gaps	2
1.3 Research Objectives	4
1.4 Contributions of the Research	4
1.5 Thesis Outline	5
CHAPTER 2. LITERATURE REVIEW	8
2.1 Introduction	8
2.2 Prototypes and the Conventional ECMs of PMSMs	9
2.3 Per-phase ECM with Predictable Core Loss	12
2.4 d - and q -axis ECM of PMSM with Predictable Core Loss	16
2.5 Core Loss Measurement.....	26
2.5.1 Core Loss Separation Method	26
2.5.2 Core Loss Direct Measurement Methods	32
2.6 Conclusion.....	37
CHAPTER 3. CORE LOSS WITH ROTATING MAGNETIC FIELDS AND EQUIVALENT RESISTANCES IN CIRCUIT MODELS	39
3.1 Introduction	39
3.2 3-D Rotating Magnetic Fields of a Claw Pole PMSM	40
3.3 Core Loss with the 3-D Rotating Magnetic Fields	55
3.3.1 1-D Alternating Core Loss	55
3.3.2 2-D Rotating Core Loss.....	55
3.3.3 3-D Rotating Core Loss.....	59
3.4 Modelling the Core Loss in the Equivalent Circuit Models	61
3.5 Parameters Identification in the ECM of the Claw Pole PMSM	65
3.5.1 Back EMF	65

3.5.2 Incremental Inductance	66
3.5.3 Stator Winding Resistance	67
3.5.4 Equivalent Core loss Resistance.....	68
3.6 Experimental Verifications of the Equivalent Core Loss Resistance in the Circuit Model.....	71
3.6.1 No-load Experimental Verifications.....	71
3.6.2 Load Experimental Verifications.....	74
3.7 Core Loss Predictable Model in the Model Predictive Control of the PMSM	77
3.7.1 Establishment of the d- and q-axis ECM with Predictable Core Loss.....	77
3.7.2 Establishment of the Drive System with Improved DPCC.....	79
3.7.3 Comparison of the Proposed and Traditional DPCC.....	81
3.8 Conclusion.....	83
CHAPTER 4. PER-PHASE EQUIVALENT CIRCUIT MODEL OF THE PMSM WITH PREDICTABLE CORE LOSS.....	85
4.1 Introduction	85
4.2 Per-phase ECM of the PMSM with Predictable Core Loss.....	87
4.3 Determination of the Equivalent Core Loss Resistances.....	89
4.4 Performance Comparisons of ECMs with Predictable Core Loss	92
4.5 Conclusion.....	99
CHAPTER 5. DQ AXIS EQUIVALENT CIRCUIT MODELS OF THE PMSM WITH PREDICTABLE CORE LOSS.....	100
5.1 Introduction	100
5.2 Analysis of the IPMSM.....	101
5.2.1 Magnetic Flux and Back EMF	102
5.2.2 Winding Resistance	104
5.2.3 Winding Inductance	104
5.2.4 Electromagnetic Torque	107
5.2.5 Core Loss.....	107
5.3 <i>d</i> - and <i>q</i> -axis ECMs of the PMSM with Predictable Core loss	109
5.4 Maximum Torque Per Ampere Current Control Considering Both the Core Loss and Copper Loss	113
5.5 Conclusion.....	118
CHAPTER 6. CONCLUSION AND FUTURE WORKS.....	119
6.1 Conclusion.....	119
6.2 Possible Future Works	120
REFERENCE	122

LIST OF FIGURES

Fig. 2-1 Prototypes of the PMSM:.....	10
Fig. 2-2 Conventional per-phase ECM of PMSM.	10
Fig. 2-4 Per-phase ECM with predictable core loss of PMSMs.....	13
Fig. 2-5 Per-phase ECM with predictable core loss of PMSMs.....	13
Fig. 2-6 ECM of PMSM with R_c as function of speed	14
Fig. 2-7 Per-phase ECM with predictable core loss of PMSMs.....	15
Fig. 2-8 Per-phase ECM with predictable core loss of PMSMs.....	15
Fig. 2-9 ECM of PMSMs with predictable core loss: (a) d -axis; (b) q -axis.....	16
Fig. 2-10 ECM of PMSMs with predictable core loss: (a) d -axis; (b) q -axis.....	19
Fig. 2-11 ECM of PMSMs considering the core loss and leakage inductance: (a) d -axis; (b) q -axis.	20
Fig. 2-12 ECM of PMSMs with predictable core loss: (a) d -axis; (b) q -axis.....	21
Fig. 2-13 ECM of PMSMs with predictable core loss: (a) d -axis; (b) q -axis.....	22
Fig. 2-14 Differential mode ECM of PMSMs with predictable core loss: (a) d -axis; (b) q -axis	23
Fig. 2-15 ECM of PMSMs with predictable core loss: (a) d -axis; (b) q -axis.....	24
Fig. 2-16 Schematic view of the no-load test.	27
Fig. 2-17 Power flow of electrical machines under no-load condition.....	27
Fig. 2-18 Schematic view of the load test with the testing PMSM working as a generator.	31
Fig. 2-19 Schematic view of the load test with the testing PMSM working as a motor.....	31
Fig. 2-20 Power flow of electrical machines under load condition.....	31
Fig. 2-21 Diagrams and photos of core loss test rig. (a) When powered by PWM inverter; (b) When powered by sinusoidal current supplier	32

Fig. 2-22 A stator core in the measurement system.....	32
Fig. 2-23 (a) Layout of the measurement setup, (b) The used instruments and one of the core sample	34
Fig. 2-24 Flux-controlled core loss tester	34
Fig. 2-25 Core loss test apparatus	35
Fig. 2-26 Magnetic circuit of the single tooth tester.....	36
Fig. 3-1 The structure of the claw pole SMC motor: (a) stator; (b) rotor.....	41
Fig. 3-2 ANSYS simulation model of one pole of the claw pole PMSM.....	42
Fig. 3-3 Magnetic flux density characteristics at point 1.....	43
Fig. 3-4 Magnetic flux density characteristics at point 2.....	44
Fig. 3-5 Magnetic flux density characteristics at point 3.....	46
Fig. 3-6 Magnetic flux density characteristics at point 4.....	47
Fig. 3-7 Magnetic flux density characteristics at point 5.....	48
Fig. 3-8 Trajectories of the flux density at point 1.	50
Fig. 3-9 Trajectories of the flux density at point 2.	51
Fig. 3-10 Trajectories of the flux density at point 3.	52
Fig. 3-11 Trajectories of the flux density at point 4.	53
Fig. 3-12 Trajectories of the flux density at point 5.	54
Fig. 3-13 Trajectories of elliptical \mathbf{B} and \mathbf{H}_l vectors.....	57
Fig. 3-14 Cross section of a three phase PMSM.....	61
Fig. 3-15 Per phase ECM of the PMSM.....	63
Fig. 3-16 Per phase ECM of the PMSM with predictable core loss.....	64
Fig. 3-17 Plots of magnetic flux density vectors.	65
Fig. 3-18 Per turn no-load flux of a phase winding.....	65
Fig. 3-19 Self-incremental, secant, and measured inductances.	67

Fig. 3-20 Measured alternating core loss of the SMC material at different frequencies.	68
Fig. 3-21 Measured rotating core loss of the SMC material at different frequencies..	69
Fig. 3-22 Equivalent core loss resistance R_c with respect to the motor speed.	70
Fig. 3-23 Experimental platform of the claw pole PMSM.	71
Fig. 3-24 Core loss measurement and calculation.	74
Fig. 3-25 Output torque versus the speed of the claw pole PMSM.	76
Fig. 3-26 ECM of PMSMs with predictable core loss: (a) d -axis; (b) q -axis.	79
Fig. 3-27 Schematic diagram of the DPCC drive system.	80
Fig. 3-28 Comparison of rotor speed response between the drive systems with the traditional and improved DPCCs.	82
Fig. 3-29 Comparison of torque response between the drive systems with the traditional and improved DPCCs.	82
Fig. 3-30 Phase current response of the drive system with the improved DPCC.	83
Fig. 4-1. Per-phase ECM of PMSM with predictable core loss.	85
Fig. 4-2. Magnetic flux density versus the phase current in the stator core of the PMSM.	86
Fig. 4-3. Generalized per-phase ECM of PMSM considering the core loss and magnetic saturation effect (In motor convention).	88
Fig. 4-5. Experimental platform of the PM TFMSM with SMC core.	93
Fig. 4-6. No-load core loss versus motor speed predicted by different methods.	94
Fig. 4-7. No-load core loss and its components versus motor speed.	95
Fig. 4-8. Core loss at the rated operating point predicted by different methods.	95
Fig. 4-9. Core loss at the rated operating point predicted by different methods.	97
Fig. 4-10. Efficiency map of the PM TFMSM.	98
Fig. 5-1. The IPMSM structure.	101
Fig. 5-2. 2D magnetic field distribution in the IPMSM.	102

Fig. 5-3. Radial and circumferential components of air-gap magnetic flux density versus rotor position.....	103
Fig. 5-4. Back EMF in per phase versus rotor position at rated speed.	103
Fig. 5-5. Incremental self-inductance of three phase windings versus rotor position at no-load condition.	105
Fig. 5-6. Incremental mutual-inductance of three phase windings versus rotor position at no-load condition.	105
Fig. 5-7. Incremental d-axis and q- axis inductances versus winding current.....	107
Fig. 5-8. Core loss of no-oriented electrical sheet steel (35WW270).....	108
Fig. 5-9. Finite-element analysis of core loss under different working speeds and phase current conditions.	109
Fig. 5-10. Comparisons of the core loss and copper loss under different speeds and currents.....	109
Fig. 5-11 ECM considering core loss and magnetic saturation effect: (a) <i>d</i> -axis; (b) <i>q</i> -axis.....	110
Fig. 5-12 Equivalent load core loss resistance versus winding current and speed in electrical angular frequency.....	112
Fig. 5-13 Schematic diagram of the stator current vector.....	114
Fig. 5-14 Schematic diagram of the improved MTPA drive system.	117
Fig. 5-15 Testing setup of the IPMSM.	117
Fig. 5-16 Measured efficiency map of the IPMSM.	117

LIST OF TABLES

Table 2-1. Comparison of the ECMs	25
Table 3-1. Dimensions and major parameters of the claw pole PMSM.	40
Table 3-2. Calculated core loss of the claw pole PMSM.....	69
Table 3-3. Power fed into the DC machine when it drives the claw pole PMSM at different speeds.	72
Table 3-4. Power fed into the DC machine when it drives the claw pole PMSM with a wooden stator.	73
Table 3-5. Measured output characteristics of the claw-pole PMSM under different load conditions.	76
Table 4-1. Parameters of the PM TFMSM.....	90
Table 4-2. Measured no-load core loss of the PM TFMSM.	91
Table 5-1 Key dimensions and design parameters	101

ABBREVIATIONS

1-D	One-dimensional
2-D	Two-dimensional
3-D	Three-dimensional
AC	Alternating current
DC	Direct current
DPCC	Deadbeat predictive current control
ECM	Equivalent circuit model
EMF	Electromotive force
EV	Electric vehicle
FEA	Finite element analysis
FEM	Finite element method
HEV	Hybrid electric vehicle
IEEE	Institute of electrical and electronics engineers
IPMSM	Interior permanent magnet synchronous motor
MPC	Model predictive controls
MTPA	Maximum torque per ampere
PI	Proportional integral
PM	Permanent magnet
PMSM	Permanent magnet synchronous motor
PWM	Pulse width modulation
RMS	Root mean square
SMC	Soft magnetic composite
SPMSM	Surface-mounted permanent magnet synchronous motor
SVPWM	Space vector pulse width modulation

TFSM	Transverse flux synchronous motor
UTS	University of Technology Sydney
VVVF	Variable voltage variable frequency

LIST OF SYMBOLS

A	Wire cross sectional area (m ²)
B	Magnetic flux density (T)
\mathbf{B}	Magnetic flux density vector (T)
b	Thickness of the electrical steel sheet (m)
B_m	Peak value of the magnetic flux density (T)
B_{maj}	Major axis of elliptical \mathbf{B} (T)
B_{min}	Minor axis of elliptical \mathbf{B} (T)
B_r	Radial magnetic flux density (T)
B_z	Axial magnetic flux density (T)
B_θ	Circumferential magnetic flux density (T)
C_{aa}	Coefficient of the alternating anomalous loss
C_{ar}	Coefficient of the rotating anomalous loss
C_e	Coefficient of the eddy current loss
C_{ea}	Coefficient of the alternating eddy current loss
C_{er}	Coefficient of the rotating eddy current loss
C_{ha}	Coefficient of the alternating hysteresis loss
E_0	Back EMF of per-phase (V)
f	Flux density frequency (Hz)
h	Coefficient of the alternating hysteresis loss
H	Magnetic field strength (A/m)
\mathbf{H}	Magnetic field strength vector (A/m)
\mathbf{H}_1	Fundamental component of magnetic field strength vector (A/m)
H_{1maj}	Major axis of elliptical \mathbf{H}_1 (A/m)
H_{1min}	Minor axis of elliptical \mathbf{H}_1 (A/m)

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

I_p	Phase current (A)
K_i	Integral coefficient
K_p	Proportion coefficient
k_{wa}	Winding factor of the phase winding
l	Total stator wire length (m)
L_{AA}	Self-inductance of phase A (H)
$L_{AB} = L_{BA}$	Mutual inductances of phase A and B (H)
$L_{AC} = L_{CA}$	Mutual inductances of phase A and C (H)
L_{BB}	Self-inductance of phase B (H)
$L_{BC} = L_{CB}$	Mutual inductances of phase B and C (H)
L_{CC}	Self-inductance of phase C (H)
L_d	d -axis inductance (H)
L_q	q -axis inductance (H)
L_s	Synchronous inductance (H)
N	Number of turns of the stator winding
n	Motor speed (r/min)
n_p	Number of phases
P_a	Alternating core loss (W)
P_{aa}	Alternating anomalous loss (W)
P_{ar}	Rotating anomalous loss (W)
P_{ea}	Alternating eddy current loss (W)
P_{em}	Electromagnetic power (W)
P_{er}	Rotating eddy current loss (W)
P_{ha}	Alternating hysteresis loss (W)
P_{hr}	Rotating hysteresis loss (W)
P_{in}	Input power (W)

P_{out}	Output power (W)
P_r	Rotating core loss (W)
R_{an}	Equivalent anomalous loss resistance at no-load conditions (Ω)
R_c	Equivalent core loss resistance (Ω)
R_e	Equivalent eddy current loss resistance at no-load conditions (Ω)
R_h	Equivalent hysteresis loss resistance at no-load conditions (Ω)
R_i	Equivalent core loss resistance at load conditions (Ω)
R_s	Stator winding resistance of one phase (Ω)
T	Time period (s)
T_{em}	Electromagnetic torque (Nm)
V_p	Phase voltage (V)
W_c	Magnetic co-energy (J)
X_s	Synchronous reactance (Ω)
η	Efficiency (%)
λ_f	Flux linkage of PMs (Wb)
ρ	Electrical resistivity of the stator winding ($\Omega \cdot m$)
ρ_m	Mass density of material (kg/m^3)
σ	Conductivity ($\Omega^{-1} \cdot m^{-1}$)
χ	Lagrange multiplier
ω_e	Rotor speed in electrical angular frequency (rad/s)
ω_m	Rotor speed in mechanical angular frequency (rad/s)