UTS UNIVERSITY OF TECHNOLOGY SYDNEY

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

by Xin Ba

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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.

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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.

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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)
$\boldsymbol{B}$	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 $\boldsymbol{B}$ (T)
B_{min}	Minor axis of elliptical $\boldsymbol{B}$ (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)
$\boldsymbol{H}$	Magnetic field strength vector (A/m)
$\boldsymbol{H}_1$	Fundamental component of magnetic field strength vector (A/m)
H_{1maj}	Major axis of elliptical $\boldsymbol{H}_1$ (A/m)
H_{1min}	Minor axis of elliptical $\boldsymbol{H}_1$ (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 (Ω·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)