New Design Methodologies for Printed Circuit Axial Field Brushless DC Motors

by

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Dissertation

Submitted in Fulfillment

of the Requirements

for the Degree of

Doctor of Philosophy

at the

The University of Southern Queensland

Faculty of Engineering & Surveying

December 2009

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2009

Abstract

A number of factors are contributing to the increased practical importance of printed circuit axial flux brushless direct current (BLDC) machines. The main ones are the availability of low cost power electronic devices and digital controllers as well as cost effective high strength permanent magnets. Advancement of multi-layer printed circuit technology is also an important factor.

Existing printed circuit board motors, found in applications such as computer disk drives and portable audio-visual equipment, are typically rated at a few watts per thousand revolutions per minute (krpm). The focus of this thesis project has been on printed circuit motors with ratings of a few tens of watts per krpm.

A significant part of this thesis project has been devoted to development of systematic design procedures for printed circuit stators. In particular those procedures include algorithms which allow performance comparisons of several stator coil shapes. A new coil shape, with improved torque capability, has been developed.

BLDC motors that operate in sensorless mode has advantages such as lower cost, better reliability and space saving. A new generalised version of the previously reported *equal inductance method* has been developed which allows sensorless commutation of printed circuit BLDC motors down to zero speed and start-up with practically no back rotation.

Computer efficient numerical models have been developed to predict phase inductances and stator eddy-current loss. Sufficiently accurate phase inductance predictions make possible theoretical assessment of performance of motors under sensorless commutation control that is based on the *equal inductance method*. The proposed method of calculation of eddy current loss allows designers to determine the track width beyond which eddy current loss becomes excessive.

The mathematical model on which the enhanced equal inductance method is based and those that have been used for performance assessment, inductance prediction and eddy-current loss evaluation have all been validated by specially designed laboratory tests carried out on prototype motors.

Certification of Thesis

I certify that the ideas, experimental work, results, analyses, software and conclusions reported in this dissertation are entirely my effort, except where otherwise acknowledged. I also certify that the work is original and has not been previously submitted for any other award, expect where otherwise acknowledged.

Signature of Candidate	Date

ENDORSEMENT

Signature of Supervisors	Date

Acknowledgments

I would sincerely like to thank and acknowledge the following people for their assistance, guidance and support throughout the duration of this thesis project.

First of all I would like to thank my supervisor Dr Tony Ahfock. Throughout the course of the research he maintained a constant interest and provided invaluable assistance and guidance in the development of this work. Much of the work developed and presented herein was discussed with and reviewed by Dr Tony Ahfock. I wish to acknowledge the significant contributions he made by in the preparation and production of this thesis.

I am also very grateful to Mr Aspesi, Mr Romano (CEO of the funding company, Metallux SA), Mr Sassone (President of the Eltek Group) and Mr Colombo for their continued support, interest in and assistance with the thesis project.

I wish to thank the Faculty of Engineering and Surveying and the Office of Research and Higher Degrees for their support and assistance. My thanks also extends to all those at the University who made this such a pleasant experience.

Finally, I wish to thank my beloved Federica, my mother, my father and my sister for their continued support.

Contents

ABSTRACT III

CERTIFICATION OF THESIS V

ACKNOWLEDGMENTS VI

CONTENTS VIII

LIST OF TABLES XIV

LIST OF FIGURES XVI

LIST OF SYMBOLS XXII

PUBLICATIONS XXX

CHAPTER 1 INTRODUCTION 1

1.1 FOCUS OF THE THESIS PROJECT 1

1.2 BACKGROUND INFORMATION ON BRUSHLESS DC MOTORS 3

1.3 BACKGROUND INFORMATION ON PRINTED CIRCUIT BLDC MOTORS 7

1.4 SENSORLESS OPERATION 14

1.5 THESIS PROJECT OBJECTIVES 15

1.6 OUTLINE OF DISSERTATION 16

1.7 MAIN OUTCOMES OF THE THESIS PROJECT 18

CHAPTER 2 LITERATURE REVIEW AND METHODOLOGY 21

2.1 LITERATURE REVIEW 21

2.1.1 Printed Circuit Motors 22

2.1.2 Sensorless Operation 26

2.1.3 Measurement of Inductances and Inductive Saliency 28

2.1.4 Prediction of Inductances and Inductive Saliency 30

2.2 METHODOLOGY 32

2.2.1 Design options and procedure 32

2.2.2 Modification and adaptation of the equal inductance method 40

CHAPTER 3 PRINTED CIRCUIT STATORS FOR BRUSHLESS PERMANENT MAGNET MOTORS 43

3.1 INTRODUCTION 43

3.2 ANALYSIS OF COIL GEOMETRIES 45

3.2.1 Purely Parallel Coils 47

3.2.2 Purely Radial Coils 50

3.2.3 Mixed Parallel and Radial Track Sections 52

3.3 PREDICTING COIL EMF'S 54

3.3.1 Approximate Analytical Modelling 56

3.3.2 Predicting Coil EMFs Numerically 59

3.4 EXPERIMENTAL VERIFICATIONS 66

3.4.1 EMF Waveforms 66

3.4.2 Thermal Considerations 69

3.4.3 Resistance Optimization 74

3.4.4 Parallel Track Sections versus Mixed Track Sections 78

3.4.5 Single Layer Machines 79

3.4.6 Number of Poles 81

3.4.7 Ratio of Inner Radius to Outer Radius 81

3.5 DESIGN OPTIMIZATION 82

3.6 CONCLUSIONS 87

CHAPTER 4 SENSORLESS COMMUTATION TECHNIQUE FOR BRUSHLESS DC MOTORS 88

4.1 INTRODUCTION 88

4.2 RELATIONSHIP BETWEEN EQUAL INDUCTANCE POSITIONS AND COMMUTATION POSITIONS 89

4.3 DETECTION OF EQUAL INDUCTANCE POSITIONS 94

4.4 INITIAL POSITION DETECTION AND START-UP 102

4.5 TEST RESULTS 106

4.6 DISCUSSION 110

4.7 CONCLUSION 111

CHAPTER 5 SENSORLESS COMMUTATION OF PRINTED CIRCUIT BRUSHLESS DC MOTORS..114

5.1 INTRODUCTION 114

5.2 CHARACTERISTICS OF TEST MOTORS 115

5.3 DETERMINATION OF COMMUTATION POSITIONS 118

5.4 INITIAL POSITION DETECTION 129

5.5 PRACTICAL INVESTIGATIONS AND TEST RESULTS 134

5.6 PRACTICAL CONSIDERATIONS 141

5.6.1 Motor Stiction 141

5.6.2 Power Semiconductor Voltage Drops Compensation 142

5.6.3 Computation Burden and Speed Range 145

5.7 CONCLUSIONS 146

CHAPTER 6 STATOR EDDY CURRENT LOSSES IN PRINTED CIRCUIT BRUSHLESS MOTORS..148

6.1 INTRODUCTION 148

6.2 CHARACTERISTICS OF TEST MOTORS 149

6.3 EDDY CURRENT MODELLING 152

6.3.1 Formulation of the Eddy Current Problem 152

6.3.2 Determination of Magnetic Flux Density Distribution 154

6.3.3 Induced Current Evaluation 156

6.3.4 Stator Track Discretization 158

6.3.5 Determination of Eddy Current Loss Distribution..161

6.4 THEORETICAL PREDICTIONS 163

6.4.1 Effect of Track Width and Number of Turns..163

6.4.2 Consideration on the Relation between Eddy Current Ripple and Axial Flux Distribution...168

6.4.3 Level of Discretisation 173

6.4.4 Effect of Substrate Position 174

6.4.5 Eddy Current Paths..175

6.4.6 Co-existence of Eddy and Load Currents...178

6.5 EXPERIMENTAL VALIDATION...180

6.6 COMPARISON BETWEEN I^{2}R AND EDDY CURRENT LOSS 184

6.7 CONCLUSION 185

CHAPTER 7 PREDICTION OF INDUCTANCES OF PRINTED CIRCUIT MOTORS 186

7.1 INTRODUCTION...186

7.2 BASIC PRINCIPLES 187

7.3 PREDICTION OF DIRECT AXIS INDUCTANCES...190

7.3.1 The Coupled Network Model...190

7.3.2 Branch Reluctance and Loop Resistances...197

7.3.3 Boundary Conditions 200

7.3.4 Magnetic Circuit Loop Analysis 202

7.4 PREDICTION OF QUADRATURE INDUCTANCES 206

7.5 CALCULATION OF MUTUAL INDUCTANCES...211

7.6 EXPERIMENTAL VALIDATION 216
7.7 CONCLUDING REMARKS 221

CHAPTER 8 CONCLUSIONS..222

8.1 THESIS PROJECT ACHIEVEMENTS 222
8.2 FUTURE WORK 227

REFERENCES 229

APPENDIX A FIRST ORDER MAGNETIC MODEL 238

A.1 THE MODEL 238
A.2 RELUCTANCE COMPUTATION 241
A.3 FLUX DENSITY COMPUTATION 243

APPENDIX B FIRST ORDER STATOR EDDY CURRENT MODEL 244

B.1 THE MODEL 244

APPENDIX C FIRST ORDER SELF INDUCTANCE MODEL 247

C.1 THE MODEL 247

APPENDIX D PHOTO GALLERY 250

D.1 PHOTOS OF HARDWARE 250

List of Tables

TABLE 2.1 : MAIN PRINTED CIRCUIT MOTOR DESIGN PARAMETERS 36
TABLE 3.1 : MOTOR TEST DATA 68
TABLE 3.2 : PRINTED CIRCUIT MOTOR DESIGN EXAMPLE 86
TABLE 4.1 : EQUAL INDUCTANCE POSITIONS AND COMMUTATION INTERVALS 92
TABLE 5.1 : COMMUTATION INTERVALS 119
TABLE 5.2: VALUE OF SENSED VOLTAGE DIFFERENCES AT FIRST COMMUTATION POSITIONS .132
TABLE 5.3 : COMMUTATION TIME MULTIPLIER Γ 140
TABLE 6.1 : TEST MOTOR DETAILS 151
TABLE 6.2 : FORCE MEASUREMENTS WIDTH DIFFERENT TRACK WIDTHS 182
TABLE 6.3 : FORCE MEASUREMENTS 183
TABLE 7.1: MEASURED AND PREDICTED SELF INDUCTANCES 217
TABLE 7.2: MEASURED AND PREDICTED MUTUAL INDUCTANCES 218
TABLE 7.3: COMPARISON BETWEEN VALUES OF K_1 TO K_5 220

TABLE B.1: TOTAL VOLUME OF COPPER WINDINGS (PER LAYER) 245

TABLE B.2: PREDICTED LOSS PER PHASE...246

List of Figures

FIGURE 1.1 : BLDC ROTORS WITH SURFACE MAGNETS (SOURCE: REFERENCE [1]) 3

FIGURE 1.2 : BLDC ROTORS WITH INTERNAL MAGNETS (SOURCE: REFERENCE [1]) 4

FIGURE 1.3 : INVERTER FED BLDC STATOR WINDINGS 5

FIGURE 1.4 : IDEALISED CURRENTS SUPPLIED BY INVERTER 6

FIGURE 1.5 : WAVE WINDING (SOURCE: REFERENCE [4]) 8

FIGURE 1.6 : RHOMBOIDAL WINDING (EXAMPLE OF A SPIRALLY SHAPED COIL) 9

FIGURE 1.7 : COILS WITH PARALLEL ACTIVE SECTIONS 10

FIGURE 1.8 : COILS WITH RADIAL ACTIVE SECTIONS 11

FIGURE 1.9 : DISTRIBUTION OF COIL ON ONE PRINTED CIRCUIT LAYER 12

FIGURE 1.10 : EXPLODED VIEW OF A PRINTED CIRCUIT AXIAL FIELD BRUSHLESS MOTOR 12

FIGURE 2.1 : GENERALISED PRINTED CIRCUIT MOTOR DESIGN OPTIMISATION FLOW-CHART .. 39

FIGURE 3.1 : (A) TOP LAYER SPIRAL (B) BOTTOM LAYER SPIRAL 46

FIGURE 3.2(A) : HALF SPIRAL SECTION OF SUBSTRATE 48

FIGURE 3.2(B) : EXAMPLE OF PRINTED COIL WITH PARALLEL TRACKS 48

FIGURE 3.3(A) : RADIAL TRACKS.. 51

FIGURE 3.3(B) : EXAMPLE OF PRINTED COIL WITH RADIAL TRACKS 51

FIGURE 3.4 : MIXED TRACK.. 53

FIGURE 3.5 : SECTION OF SUBSTRATE 54

FIGURE 3.6 : EXPLODED VIEW OF ONE OF SIX TEST MOTORS 56

FIGURE 3.7 : TRACK SEGMENT IN A CELL 60

FIGURE 3.8 : FEMLAB® MODEL OF THE ROTOR 61

FIGURE 3.9 : B-H LOOPS OF ROTOR MATERIAL 63

FIGURE 3.10 : OUTPUT FROM FINITE ELEMENT ANALYSIS 64

FIGURE 3.11 : “B” POINT “MAX SHIFT” IN DIRECTION OUTER RADIUS 65

FIGURE 3.12 : “B” POINT IN INTERMEDIATE POSITION BETWEEN OUTER AND INNER RADIUS ... 65

FIGURE 3.13 : PHASE EMF WAVEFORMS 67

FIGURE 3.14 : THE 1-D THERMAL MODEL 70

FIGURE 3.15 : PHASE A (TOP PHASE) TEMPERATURE RISE ON TIME... 73

FIGURE 3.16 : PHASES VOLTAGE DROP 74

FIGURE 3.17 : A) LAYERS STRUCTURE; B) RESISTIVE STRUCTURE... 77

FIGURE 3.18 : TORQUE CAPABILITY VERSUS NUMBER OF POLES... 78

FIGURE 3.19 : SINGLE LAYER MACHINE PHASE EMF WAVEFORM AT 1000 R/MIN................... 80

FIGURE 3.20 : SELF-INDUCTANCE L_{BB} SINGLE LAYER STATOR 80

FIGURE 3.21 : TORQUE CAPABILITY VERSUS MAGNET THICKNESS 85

FIGURE 4.1 : MEASURED SELF-INDUCTANCES 91

FIGURE 4.2 : INVERTER BRIDGE SUPPLYING A BRUSHLESS DC MOTOR................................... 93

FIGURE 4.3 : EQUIVALENT CIRCUITS FOR INVERTER STATES A^+B^- AND B^+A^- 96

FIGURE 4.4 : VOLTAGE SAMPLING INSTANTS... 97

FIGURE 4.5 : MEASURED VOLTAGE DIFFERENCES 102

FIGURE 4.6: COMMUTATION ALGORITHM BASED ON THE EQUAL INDUCTANCE METHOD 105

FIGURE 4.7(A) : ESTIMATED ROTOR POSITION 106

FIGURE 4.7(B) : POSITION ERROR 107

FIGURE 4.8 : BLDC COMMUTATION USING THE EQUAL INDUCTANCE METHOD 108

FIGURE 4.9 : BLDC COMMUTATION USING THE EQUAL INDUCTANCE METHOD 108

FIGURE 4.10 : FIRST COMMUTATION EVENT 109

FIGURE 5.1 : SELF-INDUCTANCES OF TEST MOTOR 2 116

FIGURE 5.2 : MUTUAL-INDUCTANCES OF TEST MOTOR 2 117

FIGURE 5.3 : INVERTER BRIDGE AND STATOR WINDING 119

FIGURE 5.4 : EQUIVALENT CIRCUITS FOR INVERTER STATES A^+B^- AND B^+A^- 121

FIGURE 5.5 : VOLTAGE SAMPLING INSTANTS...123

FIGURE 5.6 : RELATIONSHIP BETWEEN VOLTAGE ZERO CROSSINGS AND COMMUTATION POSITIONS 125

FIGURE 5.7 : VOLTAGE DIFFERENCE WAVEFORMS 130

FIGURE 5.8: EXPERIMENTAL VERIFICATION OF EQUATIONS 12, 14 AND 16 134

FIGURE 5.9(A) : ESTIMATED ROTOR POSITION 135

FIGURE 5.9(B) : POSITION ERROR 136

FIGURE 5.10 : COMMUTATION CONTROL ALGORITHM 138

FIGURE 5.11 : COMMUTATION UNDER LOAD AT 750 RPM, A) MOTOR 1, B) MOTOR 2...............139

FIGURE 5.12 : MOTOR 1 WAVEFORMS 141

FIGURE 5.13 : MEASUREMENTS ON MOTOR 1 144

FIGURE 6.1 : COIL SHAPE USED FOR THE MACHINE'S STATOR 150

FIGURE 6.2 : FEMLAB® MODEL OF THE ROTOR 154

FIGURE 6.3 : SUBDIVISION OF THE PRINTED COPPER TRACKS 158

FIGURE 6.4 : EXAMPLES OF LOOPS AND THE ADOPTED LOOP NUMBERING SYSTEM................162

FIGURE 6.5 : CALCULATED EDDY CURRENT LOSS FOR DIFFERENT TRACK WIDTHS 164

FIGURE 6.6 : PER TURN LOSS WITH 3.7 MM WIDE TRACKS AT 1000 RPM................................166

FIGURE 6.7 : PER TURN LOSS WITH 2.4 MM WIDE TRACKS AT 1000 RPM................................166

FIGURE 6.8 : PER TURN LOSS WITH 1 MM WIDE TRACKS AT 1000 RPM...................................167

FIGURE 6.9 : EDDY CURRENT LOSS WAVEFORMS UNDER DIFFERENT AXIAL FLUX DENSITY DISTRIBUTIONS 168

FIGURE 6.10 : BZ WITH SINUSOIDAL VARIATION IN BOTH DIRECTIONS. 169

FIGURE 6.11 : BZ WITH MODIFIED SINUSOIDAL (FLAT TOPPED) VARIATION IN RADIAL DIRECTION. 170

FIGURE 6.12 : BZ WITH MODIFIED SINUSOIDAL VARIATION IN RADIAL DIRECTION. 170

FIGURE 6.13 : BZ WITH TRAPEZOIDAL VARIATION IN THE CIRCUMFERENTIAL DIRECTION. 171

FIGURE 6.14 : BZ WITH MODIFIED SINUSOIDAL VARIATION IN RADIAL DIRECTION. 172

FIGURE 6.15 : EDDY CURRENT LOSS UNDER DIFFERENT LEVELS OF DISCRETIZATION 173

FIGURE 6.16 : CALCULATED EDDY CURRENT LOSS FOR DIFFERENT PHASES 174

FIGURE 6.17 : DIRECTION DEFINITIONS 175

FIGURE 6.18 : EDDY CURRENT DISTRIBUTION AT POSITION 0° 176

FIGURE 6.19 : TRACKS BOUNDARIES BETWEEN DIFFERENT SECTIONS 177

FIGURE 6.20 : EDDY CURRENT DISTRIBUTION AT POSITION 90° ELECTRICAL DEGREES...........178

FIGURE 6.21 : CALCULATED EDDY CURRENT LOSS FOR DIFFERENT TRACK WIDTHS 179

FIGURE 6.22 : A) CERAMIC BEARING FOR STATOR SUPPORT; B) ARRANGEMENT FOR FORCE MEASUREMENT 180

FIGURE 6.23 : BRAKING FORCE OF THE MIDDLE AND TOP PHASE AT 1000 RPM 183

FIGURE 7.1 : OVERALL PROBLEM GEOMETRY 189

FIGURE 7.2(A) : ACTUAL SPIRAL, (B): CURRENT LOOP APPROXIMATION 191

FIGURE 7.3 : MAGNETIC NODES 192

FIGURE 7.4 : GROUPING OF MAGNETIC NODES 192

FIGURE 7.5(A) : PLANAR RELUCTIVE NETWORK 194

FIGURE 7.5(B) : PLANAR RELUCTIVE NETWORK 195

FIGURE 7.5(C) : PLANAR RELUCTIVE NETWORK 196

FIGURE 7.7 : CALCULATION OF EDDY CURRENT LOOP RESISTANCES 200

FIGURE 7.8 : CALCULATION OF RADIAL DISTANCE AT BOUNDARY 201

FIGURE 7.9 : EXAMPLE OF LOOP EQUATIONS 204

FIGURE 7.10 : SELF INDUCTANCE MEASUREMENTS CARRIED OUT AT 20 KHZ WITH DIFFERENT MACHINE CONFIGURATIONS 206

FIGURE 7.11 : Q-AXIS EDDY CURRENT PATHS 207

FIGURE 7.12(A) : PLANAR RELUCTIVE NETWORK (Q-AXIS) BETWEEN 0W AND 0Z 208

FIGURE 7.12(B) : PLANAR RELUCTIVE NETWORK (Q-AXIS) BETWEEN 0Z AND 0Y 209

FIGURE 7.12(C): PLANAR RELUCTIVE NETWORK (Q-AXIS) BETWEEN 0Y AND 0X 210

FIGURE 7.13 : DETERMINATION OF MUTUAL INDUCTANCE 211

FIGURE 7.14 : FLUX DENSITY DISTRIBUTION 213

FIGURE 7.15 : CALCULATED FLUX DENSITY DISTRIBUTION DUE TO STATOR CURRENT 214

FIGURE 7.16 : CALCULATED FLUX DENSITY DISTRIBUTION DUE TO STATOR CURRENT..........215

FIGURE A.1 : MODEL GEOMETRY 239

FIGURE A.2 : MODEL GEOMETRY 240

FIGURE A.3 : SIMPLIFIED MODEL GEOMETRY..240

FIGURE A.4 : FURTHER SIMPLIFIED MODEL GEOMETRY 241

FIGURE D.1 : THE MOTOR PROTOTYPE 250

FIGURE D.2 : THERMAL MEASUREMENTS ON FIRST PROTOTYPE 251

FIGURE D.3 : SELF-INDUCTANCE MEASUREMENTS 251

List of Symbols

Chapter 2

t_i	iron axial thickness
t_m	permanent magnet axial thickness
t_{ag}	mechanical air-gap axial length
t_s	stator axial thickness
R_o	outer radius
R_i	inner radius
t_a	total axial length
t_c	stator/magnet clearance
P_l	max allowable stator power loss
B_r	remanence
B_s	rotor peak flux density
P	number of rotor poles

N	number of turns per coil
L	number of printed circuit layers per phase

Chapter 3

N	number of turns per coil
R_o	outer radius
R_i	inner radius
w	track minimum width
c	minimum clearance between tracks
N_s	number of spirals per layer
R_x	x point radius
n	number of turns counting from the inter-coil boundary line
E	EMF per spiral
ω_m	rotational speed
P	number of poles
B_{pk}	airgap peak flux density
B_r	remanence of permanent magnet.
t_m	permanent magnet axial thickness
g	airgap length measured axially between opposite magnet surfaces
S_c	combined length, spread and pitch factors of coil
B_s	maximum allowable flux density in the rotor iron
S_m	pitch factor magnet
t_i	iron axial thickness
t_s	stator axial thickness

t_a	total axial length
t_{ag}	mechanical air-gap axial length
dE	contribution to total EMF from each track segment
B*	estimated flux density at point C in figure 3.7
ω_m	rotational speed
H	magnetic field intensity
B	magnetic field density
P_l	max allowable stator power loss
R	phase resistance
R_{th} Prep-Preg	thermal resistance Pre-Preg
R_{th} FR4	thermal resistance FR4
$c_{pre\text{-}preg}$	pre-preg thermal conductivity
$c_{FR\text{-}4}$	FR-4 thermal conductivity
I_{phase}	phase current
R_{stator}	total three-phase stator resistance
α	typical heat transfer coefficient
k_f	copper fill factor
$R_{th\ S\text{-}A}$	thermal resistance surface to ambient
n_{used}	number of used layers
w_{new}	new optimized track width
k_{series}	series connection coefficient (of 2-layer elements)
EMF_{total}	total desired phase EMF
$EMF_{element}$	total EMF of 2-layer element

n_{max}	maximal number of layer
t_{layer}	layer thickness = Base cu thickness + Pre-Preg thickness
$n_{parallel}$	number of parallel layers
ρ_{Cu}	copper resistivity
l_{spiral}	length of the spiral
A_{spiral}	cross sectional area of the spiral

Chapter 4

L_{ii}	self inductance of phase i;
L_{ji}	mutual inductance between phase i and phase j
E_i	i-phase winding back EMF
v_{cy}	voltage measurements between phase c and rail y
v_{cy}^{+}	voltage measurements in states a^+b^-
v_{cy}^{-}	voltage measurements in states b^+a^-
v_{ay}	voltage measurements between phase a and rail y
v_{by}	voltage measurements between phase b and rail y
t_s^{+}	sampling instant during on pulse
t_s^{-}	sampling instant during “off” pulse
V_{dc}	dc bus voltage
V_t	switching device voltage drop
L_q	q-axis inductance

L_d	d-axis inductance
S	saliency ratio
θ_i	rotor initial position

Chapter 5

L_{ii}	self inductance of phase i ;
L_{ji}	mutual inductance between phase i and phase j
E_i	i-phase winding back EMF
v_{cy}	voltage measurements between phase c and rail y
v_{cy}^{+}	voltage measurements in states a^+b^-
v_{cy}^{-}	voltage measurements in states b^+a^-
v_{by}	voltage measurements between phase b and rail y
v_{by}^{+}	voltage measurements in states a^+c^-
v_{by}^{-}	voltage measurements in states c^+a^-
v_{ay}	voltage measurements between phase a and rail y
v_{ay}^{+}	voltage measurements in states b^+c^-
v_{ay}^{-}	voltage measurements in states c^+b^-
t_s^{+}	sampling instant during on pulse
t_s^{-}	sampling instant during “off” pulse

v_{dc}	dc bus voltage
θ_i	rotor initial position
t_{ON}	on time of the PWM pulse
t_{OFF}	off time of the PWM pulse
R_{DSon}	dynamic resistance of power semiconductor

Chapter 6

H	magnetic flux intensity
J	current density
E	electric field induced within printed tracks
B	magnet flux density
J_i	imposed current density
J_e	induced current density
J_m	magnetisation current density
μ	magnetic permeability
σ	electric conductivity
M	magnetisation of permanent magnets
$B(r, \theta, z, t)$	flux density seen, at time t, by an observer fixed to the stator at location (r, θ, z)
ω	speed of the rotor
B_z	component of flux density normal to the conductor plane
v	relative speed between the magnetic field and the conductor
λ	angle between the conductor and the direction of relative motion
R_{ia}	resistance of internal branch along the track

R_{ea}	resistance of branch along the track on the grid edge
R_{ib}	resistance of internal branch across the track
R_{eb}	resistance of branch across the track on the edge of the grid
w_s	width of segment
w_f	width of filament
t_c	track thickness
σ	electrical conductivity of track
I_{loop}	array of loop currents
E_{loop}	array of loop EMFs
R_{loop}	loop resistance matrix
I_{branch}	array of branch currents
A	loop to branch incidence matrix
R	resistance of a track section
I	motor current
I_e	eddy current
P_e	eddy current loss
T_e	rotor driving torque
ω	the rotor speed
L_a	length of the torque arm
F_rL_a	bearing friction torque

Chapter 7

L_z	axial separation
A_z	area between conductor loops

μ	permeability of material
L_r	mean separation between inter-conductors mid-lines
A_r	(conductor perimeter) x (axial separation)
R	reluctance
σ	conductivity of the magnet
L_x	weighted average of all discrete distances between the last stator conductor that falls fully within the magnet profile and the edge of the magnet
A_{cell}	area of the cell
L_{ii}	self inductance of phase i ;
L_{ji}	mutual inductance between phase i and phase j
L_{da}	direct axis self-inductance of phase a
L_{db}	direct axis self-inductance of phase b
L_{qa}	quadrature axis self-inductance of phase a
L_{qb}	quadrature axis self-inductance of phase b
M_{bd}	mutual inductances ab when phase ‘a’ is aligned with the rotor d-axis
M_{cd}	mutual inductances ac when phase ‘a’ is aligned with the rotor d-axis
M_{bq}	mutual inductances ab when phase ‘a’ is aligned with the rotor q-axis
M_{cq}	mutual inductances ac when phase ‘a’ is aligned with the rotor q-axis

Publications

The following journal papers, that have been published or accepted for publication, are direct outcomes of this research project.

Ahfock A.**,** Gambetta D., ‘*Stator Eddy Current Losses in Printed Circuit Brushless DC Motors*’, Electric Power Applications, IET Proceedings, (accepted for publication)

Ahfock A.**,** Gambetta D., ‘*Sensorless Commutation of Printed Circuit Brushless DC Motors*’, Electric Power Applications, IET Proceedings, (accepted for publication)

Gambetta D., Ahfock A., ‘*Design of Printed Circuit Brushless Motors*’, Electric Power Applications, IET Proceedings, Vol 3, Issue 5, Sept 2009, Pages 482-490

Gambetta D., Ahfock A., ‘*A New Sensorless Commutation Technique for Brushless DC Motors’*, Electric Power Applications, IET Proceedings, Vol 3, Issue 1, Jan 2009, Pages 40-49