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Zi Qiang Zhu, Xi Meng Wu

Sensorless Control of Permanent Magnet Synchronous Machine Drives

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About the Authors

Professor Zi Qiang Zhu received the BEng and MSc degrees from Zhejiang University, Hangzhou, China, in 1982 and 1984, respectively, and the Ph.D. degree from The University of Sheffield, Sheffield, U.K., in 1991, all in electrical engineering.

After working as Lecturer/Assistant Lecturer at Zhejiang University from 1984 to 1988, he has been with The University of Sheffield since 1988, initially as Visiting Research Fellow sponsored by the British Council (1988–1989), then Research Associate working with Philips (1989-1992), Senior Research Scientist/Officer––an established university post (1992–2000), Professor (2000–present), Royal Academy of Engineering/Siemens Research Chair (2014–present), and Head of the Electrical Machines and Drives Research Group (2008–present). As the Founding Director, he has helped several industries in establishing their research centers, most notably, Siemens Gamesa Renewable Energy Research Center at Sheffield (2009–present) and Midea Electrical Machines and Control Research Centers at Shanghai and Sheffield (2010–present).

His research interests include design and control of permanent magnet brushless machines and drives for applications ranging from electrified transportation (electric vehicles, fast trains, and more electric aircraft) to domestic appliances to wind power generation. He has published more than 1400 papers, including more than 550 for IEEE Transactions and IET Proceedings.

He is a Fellow of the Royal Academy of Engineering, UK; Institute of Electrical and Electronics Engineers (IEEE), USA; Institution of Engineering and Technology (IET), UK; and Chinese Society for Electrical Engineering (CSEE), China. He is the recipient of the 2019 IEEE Industry Applications Society Outstanding Achievement Award and the 2021 IEEE Nikola Tesla Award.

Dr Xi Meng Wu received the BEng degree in electrical engineering and automation from Hefei University of Technology, Hefei, China, in 2011, and MSc and PhD degrees in electrical engineering from The University of Sheffield,

Sheffield, UK in 2016 and 2020, respectively. Since 2020, he has been a Postgraduate Research Associate at the University of Sheffield associated with the Sheffield Siemens Gamesa Renewable Energy Research Centre. His research interests include control of permanent magnet synchronous machines.

Preface

Permanent magnet (PM) synchronous machine (PMSM) drives, including PM brushless ac and dc drives, exhibit many advantages such as high efficiency and high torque density. A high-performance PM brushless ac or dc drive needs accurate rotor position information. This is usually obtained by using a hardware rotor position sensor, such as a resolver, encoder, or Hall sensor. However, these sensors increase drive size and cost and reduce reliability, particularly in harsh environments. Therefore, it is desirable to replace hardware rotor position sensors with software-based rotor position sensorless techniques.

This book aims to comprehensively describe sensorless control techniques of PMSM drives. We have strived to highlight the global research achievements and also many new techniques developed at the University of Sheffield. The basic principles and state-of-the-art rotor position sensorless control techniques are explained, together with their challenges and practical solutions. The scope is very broad, and readers may find the summary diagram in section 1.7 useful.

Thirty years ago, sensorless control of PMSM drives had limited application and was mostly used for driving ventilation fans with brushless dc drives. However, over the last 10 years, the field has rapidly expanded. Today, numerous commercial products are using sensorless control techniques for a wide variety of applications, for example wind power generators, automotive compressors, water and oil cooling pumps, electric bicycles, drones, general purpose variable frequency drives, and household appliances (e.g. air-conditioning and refrigerator compressors and fans, washing machines, dishwasher pumps, heat circulating pumps, and vacuum cleaners), as well as fault-tolerance drives in electrified transportation and aerospace applications. Despite these successes, the use of sensorless control for applications that require high torque for rapid starting remains challenging. As the technology continues to evolve and improve, it is likely that sensorless control will find even broader applications, offering a reliable, cost-effective, and efficient solution for a wide range of industrial and commercial needs.

Beginning in 1998, I have been working with my PhD students on various topics of sensorless control of PMSM drives. I would like to take this opportunity to thank them for their contributions, including J. Ede, J. X. Shen, Y. F. Shi, Y. Liu, Y. Li, L. M. Gong, J. M. Liu, T. C. Lin, A. H. Almarhoon, P. L. Xu, H. L. Zhan, X. M. Wu, L. Yang, B. Shuang, and T. Y. Liu. In particular, Dr. Xi Meng Wu, currently a post-doctoral researcher at the University of Sheffield and the co-author of this book, has made significant contributions to sensorless control, especially the novel techniques for initial rotor position detection.

I would like to acknowledge the pioneering work on sensorless control of PMSM drives by Professor Robert D. Lorenz at University of Wisconsin-Madison, USA, Professor Seung-Ki Sul at Seoul National University, South Korea, and Professor Fernando Briz and Professor David Reigosa at University of Oviedo, Spain, as well as Professor Nobuyuki Matsui, Dr. Zhiqian Chen, Professor Shigeo Morimoto, Professor Ion Boldea, and Professor Kaushik Rajashekara, and others.

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My co-author and I sincerely hope this book will be useful to industrial engineers and researchers, university professionals, post-doctoral researchers, and students alike.

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FREng, FIEEE, FIET, FCSEE
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List of Abbreviations

ac	Alternating current
AD	Analog to digital
ADC	Analog-to-digital converter
AF	Active flux
ANF	Adaptive notch filter
BDS	Boundary selection strategy
BLAC	Brushless ac
BLDC	Brushless dc
BPF	Band-pass filter
CCS-MPC	Continuous-control-set model predictive control
CM	Current model
CMV	Common mode voltage
CPU	Central processing unit
dc	Direct current
DEA	Differential evolution algorithm
DFT	Discrete Fourier transform
DQZ	Direct-quadrature-zero
DSP	Digital signal processor
DTC	Direct torque control
DTP-PMSM	Dual three-phase permanent magnet synchronous machine
EEMF	Extended electromotive force
EKF	Extended Kalman filter
EMF	Electromotive force
FCS-MPC	Finite-control-set model predictive control
FE	Finite element
FEA	Finite element analysis
FO	Flux-linkage observer
FOC	Field oriented control
HF	High frequency
HPF	High-pass filter

INFORM	Indirect flux detection by online reactance measurement
IPM	Interior PM
IPMSM	Interior permanent magnet synchronous machine
LDF	Lower-diode freewheeling
LMS	Least-mean-squares
LPF	Low-pass filter
LUT	Look-up table
MMF	Magneto-motive force
MPC	Model predictive control
MRAS	Model reference adaptive system
MTPA	Maximum torque per ampere
OW-PMSM	Open-winding permanent magnet synchronous machine
PI	Proportional integral
PLL	Phase-locked loop
PM	Permanent magnet
PMSM	Permanent magnet synchronous machine
PO	Position observer
PWM	Pulse width modulation
QSG	Quadrature signal generator
RSA	Reliable selection area
RVD	Resistance voltage divider
SMO	Sliding mode observer
SNR	Signal-to-noise ratio
SOA	Safe operating area
SOGI	Second order generalized integrator
SPM	Surface-mounted PM
SPMSM	Surface-mounted permanent magnet synchronous machine
SSOA	Sensorless safe operation area
STP-PMSM	Single three-phase permanent magnet synchronous machine
SVPWM	Space vector pulse width modulation
THD	Total harmonic distortion
UDF	Upper-diode freewheeling
VC	Vector control
VM	Voltage model
VSD	Vector space decomposition
VSI	Voltage source inverter
ZCD	Zero-crossing detection
ZCP	Zero-crossing point
ZSC	Zero sequence current
ZSV	Zero sequence voltage
ZVC	Zero vector current
ZVCD	Zero vector current derivative

List of Symbols

Symbol	Description	Unit
A_{ac}	Amplitude of injected ac current reference	A
$A_{d,2f}$, $A_{q,2f}$	Amplitudes of second order harmonic of *d*- and *q*-axis estimated back-EMFs	V
A_{mp}	Amplitude of third harmonic flux-linkage	Wb
$Amp\_i_{\mathrm{A}h}$, $Amp\_i_{\mathrm{B}h}$, $Amp\_i_{\mathrm{C}h}$	Amplitudes of three-phase HF currents	A
B	Viscous damping factor	Ns/m
B_3	Amplitude of third harmonic component of excitation flux density	T
D	Duty ratio	
$E_{\mathrm{A}}(s)$, $E_{\mathrm{B}}(s)$, $E_{\mathrm{C}}(s)$	Three-phase back-EMFs after Laplace transform	V
e_{A}, e_{B}, e_{C}	Three-phase back-EMFs	V
e_{A5}, e_{B5}, e_{C5}	Three-phase fifth order harmonic back-EMFs	V
e_{A7}, e_{B7}, e_{C7}	Three-phase seventh order harmonic back-EMFs	V
$E_{a,d}$, $E_{a,q}$	*dq*-axis back-EMFs of active flux model	V
e_c	Back-EMF of current model	V
$\hat{E}_d$, $\hat{E}_q$	Estimated *d*- and *q*-axis back-EMFs	V
$\hat{E}_{d0}$, $\hat{E}_{q0}$	dc components of *d*- and *q*-axis estimated back-EMFs	V
$\hat{E}_{d,2f}$, $\hat{E}_{q,2f}$	Second order harmonic of *d*- and *q*-axis estimated back-EMFs	V
E_{ex}	Extended back-EMF	V

(*Continued*)

(Continued)

Symbol	Description	Unit
$\hat{E}_{ex,d}$, $\hat{E}_{ex,q}$	Estimated *d*- and *q*-axis extended back-EMFs	V
E_{ex_imp}	Improved extended back-EMF	V
E_{ex1}	Equivalent extended back-EMF of DTP-PMSM	V
$e_{ex,\alpha}$, $e_{ex,\beta}$	α- and β-axis extended back-EMFs	V
e_{H}, e_{L}, e_{O}	High-level, low-level, and floating phase back-EMFs	V
E_m	Peak value of phase back-EMF	V
E_{m3}	Amplitude of third harmonic back-EMF	V
e_α, e_β	α- and β-axis back-EMFs	V
e_0	Zero sequence back-EMF	V
$\hat{e}_0$	Estimated zero sequence back-EMF	V
E_3	Amplitude of third harmonic back-EMF	V
e_{3_set1}, e_{3_set2}	Third harmonic back-EMFs in two sets	V
e_{3_set1}, e_{9_set1}, e_{15_set1}	Third, ninth, and fifteenth harmonic back-EMFs of first set of DTP-PMSM	V
e_{3_set2}, e_{9_set2}, e_{15_set2}	Third, ninth, and fifteenth harmonic back-EMFs of second set of DTP-PMSM	V
e_9	Ninth order harmonic back-EMF	V
e_{15}	Fifteenth order harmonic back-EMF	V
f_e	Electrical rotor frequency	Hz
f_h	Frequency of injected high-frequency voltage signal	Hz
$f(\Delta\theta)$	Position error signal	
I^*	Amplitude of extra injected current signal	A
$I_{\mathrm{A}}(s)$, $I_{\mathrm{B}}(s)$, $I_{\mathrm{C}}(s)$	Three-phase currents after Laplace transform	A
i_{A}, i_{B}, i_{C}	Three-phase stator currents	A
I_A^P, I_B^P, I_C^P	Three-phase primary current response peak values	A
I_A^S, I_B^S, I_C^S	Three-phase secondary current response peak values	A
$i_{\mathrm{ABC}h}$	Three-phase high-frequency current responses	A
I_{AD_error}	Disturbance current vector due to current measurement error	A
I_d, I_q	Amplitudes of *dq*-axis currents	A
i_d, i_q	*d*- and *q*-axis currents	A
$\hat{i}_d$, $\hat{i}_q$	Estimated *d*- and *q*-axis currents	A
i_{dc}	dc-link current	A

(Continued)

Symbol	**Description**	**Unit**
i_{dc}^{*}	dc-link current reference	A
$\hat{i}_{d,ac}$, $\hat{i}_{q,ac}$	Estimated *d*- and *q*-axis ac current components	A
$i_{d,CM}$, $i_{q,CM}$	*d*- and *q*-axis currents of current model	A
$\hat{i}_{d,dc}$, $\hat{i}_{q,dc}$	Estimated *d*- and *q*-axis dc current components	A
i_{df}, i_{qf}	Fundamental *d*- and *q*-axis currents	A
$\hat{I}_{dh}$, $\hat{I}_{qh}$	Amplitudes of estimated *dq*-axis high-frequency currents	A
i_{dh}, i_{qh}	*d*-and *q*-axis high-frequency currents	A
$\hat{i}_{dh}$, $\hat{i}_{qh}$	Estimated *d*- and *q*-axis high-frequency currents	A
i_{dh}^{v}, i_{qh}^{v}	Virtual *d*- and *q*-axis high-frequency currents	A
i_{dq}^{*}	References of *d*- and *q*-axis currents	A
i_{dq}^{p}	Predicted *d*- and *q*-axis currents	A
ΔI_{error}	Error between real and recorded currents	A
$i_{(Extra)}^{*}$	Extra injected current signal	A
i_{H}, i_{L}, i_{O}	High-level, low-level, and floating phase currents	A
I_m	Peak value of phase current	A
$I_{\max}$	Maximum current response peak value	A
I_{mean}	Average current response peak value	A
I_n	Amplitude of negative sequence current response	A
i_n	Negative sequence current response	A
$\hat{i}_n$	Estimated negative sequence current response	A
I_n^{SQ}	Amplitude of negative sequence current response of square-wave injection	A
$\hat{i}_{nd}$, $\hat{i}_{nq}$	Estimated *d*- and *q*-axis negative sequence current responses	A
I_{neg_α}, I_{neg_β}	α- and β-axis components of negative sequence HF current	A
I_p	Amplitude of positive sequence current response	A
i_p	Positive sequence current response	A
I_p^{SQ}	Amplitude of positive sequence current response of square-wave injection	A

(*Continued*)

(Continued)

Symbol	Description	Unit
I_{pos_α}, I_{pos_β}	α- and β-axis components of positive sequence HF current	A
I_{q_MAX}	Maximum q-axis current	A
I_{qu}	Quantum current of analog-to-digital converter	A
I_{real}	Real current	A
I_{record}	Recorded current	A
I_s	Amplitude of stator current	A
i_s	Stator currents	A
ΔI_{th}	Threshold current value	A
i_X, i_Y, i_Z	Phase currents of second winding set of DTP-PMSM	A
i_{Xf}	Fundamental current in arbitrary phase	A
i_{Xh}	High-frequency current in arbitrary phase	A
i_{z1z2}	Stator current in z_1z_2 subspaces	A
i_α, i_β	α- and β-axis currents	A
$\hat{i}_\alpha$, $\hat{i}_\beta$	α- and β-axis estimated currents	A
Δi_α, Δi_β	α- and β-axis current estimation errors	A
$I_{\alpha\beta h}$	Amplitudes of α-and β-axis high-frequency currents	A
$i_{\alpha\beta h}$	α- and β-axis high-frequency currents	A
$i^*_{\alpha\beta h}$	α- and β-axis high-frequency currents before compensating positive current	A
$i^{**}_{\alpha\beta h}$	α- and β-axis high-frequency currents after compensating for positive current	A
I_0	Amplitude of dc component of three-phase current responses	A
i_0	Zero sequence current	A
I_2	Amplitude of second order harmonic component of three-phase current responses	A
i_{2nd}	Secondary positive sequence harmonics in HF current response	A
J	Inertia	kg.m^2
k_c	Compensation factor for cross-coupling inductances	mH/A
K_i	Integration gain of PI controller	
$K_{\Delta L_q}$	Deviation factor of q-axis inductance	rad/A
$K_{\Delta L_{q1}}$	Deviation factor of q-axis self-inductance in Set 1	rad/A

(Continued)

Symbol	Description	Unit
$K_{\Delta M_{q21}}$	Deviation factor of q-axis mutual-inductance between two sets	rad/A
K_p	Proportional gain of PI controller	
k_{p3}, k_{d3}, k_{s3}	Coil pitch factor, distribution factor, and skew factor for third harmonic	
K_{R}	Equivalent gain of resistance voltage divider	
k_r	Compensation factor for cross-coupling error angle	rad/A
$K_{\Delta R_s}$, $K_{\Delta L_Q}$	Deviation factors of resistance and q-axis equivalent inductance	rad/A
k_{w3}	Winding factor for third harmonic	
K_ω	Slope of back-EMF envelope around ZCP	V
L	Phase self-inductance of BLDC	mH
ΔL	Asymmetric inductance	mH
L_{AA}, L_{BB}, L_{CC}	Three-phase self-inductances	mH
ΔL_{AB}, ΔL_{BC}, ΔL_{CA}	Three-phase inductance asymmetric errors of BLDC	mH
L_c	Second order harmonic amplitude of sine inductance term in self-inductance	mH
L_D, L_Q	Equivalent d- and q-axis inductances of DTP-PMSM	mH
L_d, L_q	d- and q-axis self-inductances	mH
$\tilde{L}_d$, $\tilde{L}_q$	Nominal values of d- and q-axis inductances	mH
ΔL_d, ΔL_q	Mismatch values of d- and q-axis inductances	mH
L_{dh}, L_{qh}	dq-axis incremental self-inductances	mH
L_{dq}, L_{qd}	Cross-coupling dq-axis inductances	mH
L_{dqh}, L_{qdh}	Cross-coupling dq-axis incremental inductances	mH
L_{d1}, L_{d2}, L_{q1}, L_{q2}	d- and q-axis self-inductances of two winding sets	mH
L_{eq}	Equivalent inductance	mH
L_{H}, L_{L}	High- and low-level inductances	mH
$L_{\Delta h}$	Amplitude of hth spatial inductance	mH
L_{lm}	Boundary inductance	mH
L_{ls}	Leakage self-inductance	mH
L_{MAX}, L_{MIN}	Maximum and minimum inductances	mH

(*Continued*)

(Continued)

Symbol	Description	Unit
L_n	Negative sequence inductance	mH
L_p	Positive sequence inductance	mH
L_{qds}	Approximated cross-coupling inductances	mH
L_{sa}	Average between *d*- and *q*-axis incremental inductances	mH
L_{sd}	Difference of *d*- and *q*-axis incremental inductances	mH
L_{sj}, L_{sk}	*j*th and *k*th order self-inductances	mH
L_{s0}	Average value of self-inductance	Wb
L_{s2}	Amplitude of second order harmonic component of self-inductance	Wb
L_{XX}, L_{YY}, L_{ZZ}	Three-phase self-inductances of first winding set in DTP-PMSM	mH
$L_{\alpha\alpha}$, $L_{\beta\beta}$	*α*- and *β*-axis self-inductances	mH
L_0	Zero sequence inductance	mH
M	Phase mutual-inductance of BLDC	mH
M_{AB}, M_{BA}, M_{AC}, M_{CA}, M_{BC}, M_{CB}	Three-phase mutual-inductances	mH
M_c	Second order harmonic amplitudes of sine inductance terms in mutual-inductances	mH
M_{d12}, M_{d21}, M_{q12}, M_{q21}	*d*- and *q*-axis mutual-inductances between two winding sets	mH
ΔM_{q21}, ΔM_{q12}	Deviation values of *q*-axis inductances between two sets	mH
M_{sj}, M_{sk}	*j*th and *k*th order mutual-inductances	mH
M_{s0}	Average value of mutual-inductance	Wb
M_{s2}	Second order harmonic of mutual-inductance	Wb
M_{XY}, M_{YX}, M_{YZ}, M_{ZY}, M_{ZX}, M_{XZ}	Three phase mutual-inductances of second winding set in DTP-PMSM	mH
$M_{\alpha\beta}$, $M_{\beta\alpha}$	*α*- and *β*-axis mutual-inductances	mH
N_s	Number of sample points	
$P(k)$	Covariance matrix of EKF	
P	Number of pole pairs	
p	Derivative operator	
$Q(k)$, $R(k)$	Covariances of process noise and measurement noise of EKF	
R	Phase resistance of BLDC	Ω
ΔR_{A}, ΔR_{B}, ΔR_{C}	Asymmetric resistances components	Ω

(Continued)

Symbol	Description	Unit
ΔR_{ave}	dc offset due to resistance asymmetry	Ω
R_d, R_q	d- and q-axis resistances	Ω
R_{dc}	dc-link resistance	Ω
R_{dq}	dq-axis mutual-resistance	Ω
R_{eq}	Equivalent resistance	Ω
R_N	Resistance of auxiliary resistor network	Ω
R_s	Phase resistance	Ω
$\tilde{R}_s$	Nominal value of phase resistance	Ω
$\overline{R}_s$	Balanced part of three-phase resistances	Ω
ΔR_s	Mismatch value of phase resistance	Ω
$R_{\mathrm{X}h}$	Equivalent HF resistance of inverter in arbitrary phase	Ω
R_1, R_2	Nominal values of low and high side resistances of resistance voltage divider	Ω
R_1', R_2'	Actual values of low and high side resistances of resistance voltage divider	Ω
$\boldsymbol{S}$	Sliding mode surface	
$\mathrm{S_A}$, $\mathrm{S_B}$, $\mathrm{S_C}$	Switching states of three legs of VSI	
t	Time	s
ΔT	Period of injected square-wave voltage signal	s
Δt	Time step	s
T_c	Time constant of LPF	s
t_d	Time interval of half cycle between two zero-crossing points	s
t_{dd}	Turn-off delay of power device	s
t_{dt}	Deadtime	s
t_{du}	Turn-on delay of power device	s
T_{inj}	Period of extra injected current signal	s
T_{i1}, T_{i2}	Periods of first and second injected HF voltage signals	s
T_L	Load torque	Nm
T_{m_BLAC}	Electromagnetic torque of a BLAC machine	Nm
T_{m_BLDC}	Electromagnetic torque of a BLDC machine	Nm
T_{opt}	Optimal duration of voltage pulse	s
T_P	Duration of voltage pulse	s
t_{period}	Fundamental period	s

(*Continued*)

(Continued)

Symbol	Description	Unit
T_{P_MAX}, T_{P_MIN}	Maximum and minimum durations of voltage pulse	s
t_r	Remainder of division of time by injection period	s
T_s	Sampling period	s
$t_\varphi[n]$	nth time delay for commutation instant	s
$t_\theta[n]$	nth ZCP time interval	s
T_0	Duration of zero voltage vector	s
T_1	Duration of voltage vector 1	s
T_2	Duration of voltage vector 2	s
t_{23}, t_{34}, t_{45}, t_{25}, t_{52}, t_{56}, t_{61}, t_{12}	Period between sectors	s
u_{VA}, u_{VB}, u_{VC}	Three-phase vertical error correction common-mode bias	V
u_1, u_2, u_3, u_4, u_5, u_6	Zero-crossing thresholds	V
ΔV	Average terminal voltage error	V
v_{A}, v_{B}, v_{C}	Three-phase stator voltages	V
Δv_{AB}, Δv_{BC}, Δv_{CA}	Three-phase horizontal voltage shifts	V
V_{AD}	Maximum sampling voltage	V
$V_{\mathrm{AG}}(s)$, $V_{\mathrm{BG}}(s)$, $V_{\mathrm{CG}}(s)$	Three-phase terminal voltages after Laplace transform	V
v_{AG}, v_{BG}, v_{CG}	Voltage between phase terminal and ground	V
$v_{\mathrm{A}h}$, $v_{\mathrm{B}h}$, $v_{\mathrm{C}h}$	Injected three-phase HF voltages	V
v_{AN}, v_{BN}, v_{BN}	Phase voltages of a PM machine in ABC reference frame	V
v'_{BG}	Acquired phase B terminal voltage	V
V_c	Amplitude of equivalent voltage source	V
v_d, v_q	d- and q-axis voltages	V
$\hat{v}_d$, $\hat{v}_q$	Estimated d- and q-axis voltages	V
V_{dc}	dc-link voltage	V
ΔV_{dc}	dc-link voltage variation	V
$\hat{v}_{d\_ff}$	Estimated d-axis feed-forward voltage	V
v_{dh}, v_{qh}	d- and q-axis high-frequency voltages	V
$\hat{v}_{dh}$, $\hat{v}_{qh}$	Estimated d- and q-axis high-frequency voltages	V
v^v_{dh}, v^v_{qh}	Virtual d- and q-axis high-frequency voltages	V
v_{dh1}, v_{dh2}	First and second injected HF voltage signals	V
$\hat{v}_{d,VM}$, $\hat{v}_{q,VM}$	Voltages of voltage model	V