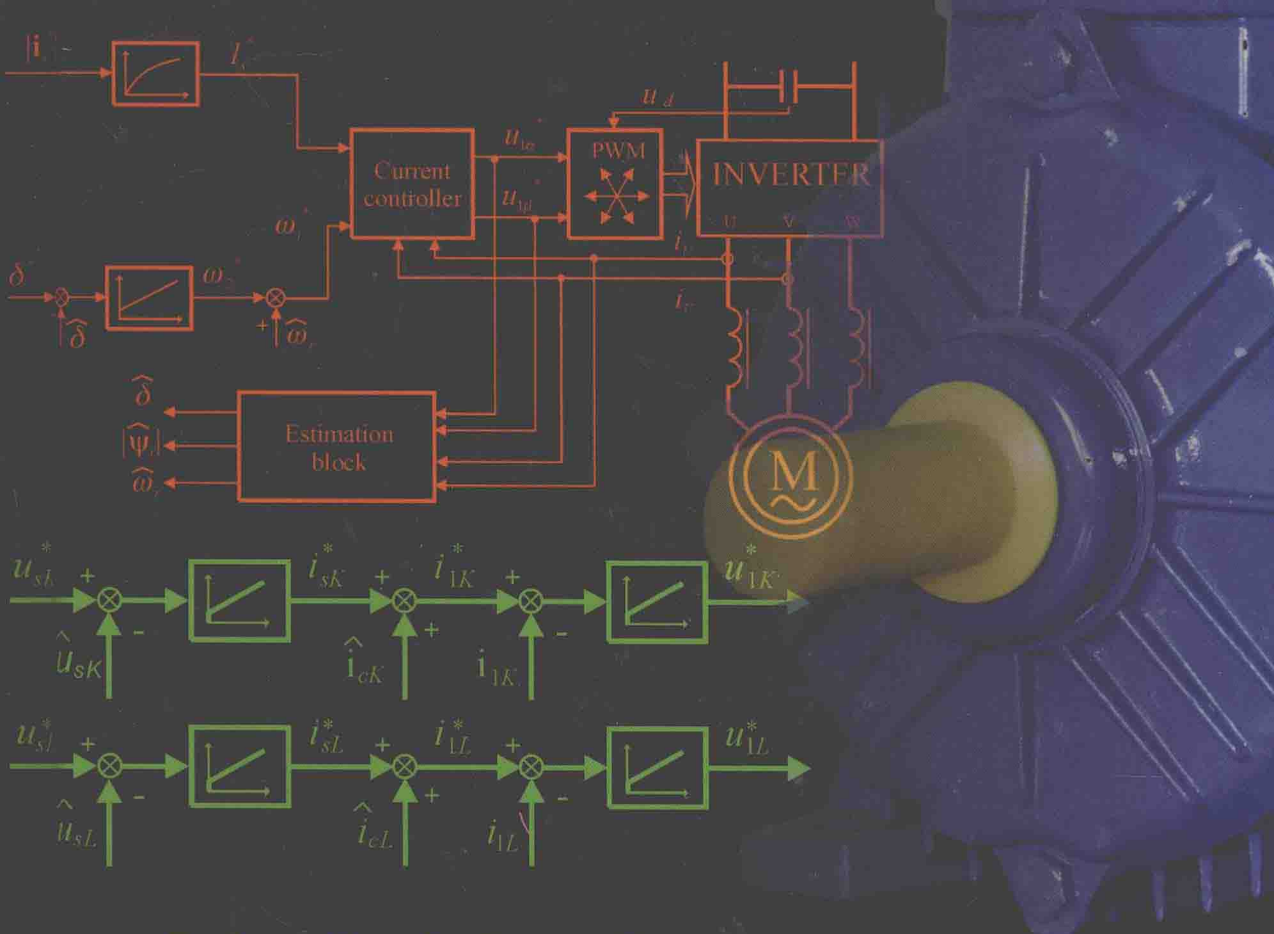

Variable Speed AC Drives with Inverter Output Filters

Jaroslaw Guzinski · Haitham Abu-Rub · Patryk Strankowski

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Dedicated to my parents, my wife Anna and my son Jurek
—Jaroslaw Guzinski

Dedicated to my parents, my wife Beata, and my children Fatima, Iman,
Omar, and Muhammad
—Haitham Abu-Rub

Dedicated to my parents Renata and Władysław, and
my girlfriend Magdalena
—Patryk Strankowski

Foreword

The converter-fed electric drive technologies have grown fast and matured notably over the last few years through the advancement of technology. Therefore, it is my great pleasure that this book, *Variable Speed AC Drives with Inverter Output Filters*, will perfectly fill the gap in the market related to design and modern nonlinear control of the drives fed from the inverters equipped with output filters. Such filters are installed mainly for reducing high dv/dt of inverter pulsed voltage and achieving sinusoidal voltage and currents waveforms (sinusoidal filter) on motor terminals. As a result, noises and vibrations are reduced and the motor efficiency is increased. These advantages, however, are offset by the complication of drive control because with inverter output filter there is a higher order control plant.

The book is structured into ten chapters and five appendices. The first chapter is an introduction, and general problems of AC motors supplied from voltage source inverter (VSI) are discussed in Chapter 2. The idealized complex space-vector models based on T and Γ equivalent circuits and its presentation in state space equations form for the AC induction machine are derived in Chapter 3. Also, in this chapter, definitions of per-unit system used in the book are given. The detailed overview, modeling, and design of family of filters used in inverter-fed drives: sinusoidal filter, common mode filter, and dV/dt filter are presented in Chapter 4. Next, in Chapter 5, several types of state observers of induction machine drive with output filter are presented in detail. These observers are necessary for in-depth studies of different sensorless high-performance control schemes presented in Chapter 6, which include: field oriented control (FOC), nonlinear field oriented control (NFOC), multiscalar control (MC), direct load angle control (LAC), direct torque control with space vector pulse width modulation (DTC-SVM). Chapter 7, in turn, is devoted to current control and basically considers the model predictive stator current control (MPC) of the induction motor drive with inductive output filter implemented and investigated by authors. A difficult, but important issue of fault diagnosis in the induction motor drives (broken rotor bars, rotor misalignment, and eccentricity) are studied in Chapter 8, which presents methods based on frequency analysis and artificial intelligence (NN) and adaptive neuro-fuzzy inference system (ANFIS). In Chapter 9, the results of analyzing, controlling, and investigating the classical three-phase drives with inverter output filter are generalized for five-phase inductive machines, which are characterized by several important advantages such as higher torque density, high fault tolerance, lower torque pulsation and noise, lower current losses, and reduction of the rated current of power converter devices. Chapter 10 gives a short summary and final conclusions that underline the main topics and achievements of the book. Some special aspects are presented in appendices (A to F): synchronous sampling of inverter current (A), examples of LC filter design (B), transformations of equations (C), motor data used in the book (D), adaptive back stepping observer (E), and significant variables and functions used in simulation files (F).

This book has strong monograph attributes and discusses several aspects of the authors' current research in an innovative and original way. Rigorous mathematical description, good illustrations, and a series of well-illustrated MATLAB®-Simulink models (S Functions written in C language included). Simulation results in every chapter are strong advantages which makes the book attractive for a wide spectrum of researches, engineering professionals, and undergraduate/graduate students of electrical engineering and mechatronics faculties.

Finally, I would like to congratulate the authors of the book because it clearly contributes to better understanding and further applications of converter-fed drive systems.

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Above all, we are grateful to the almighty, the most beneficent and merciful who provides us confidence and determination in accomplishing this work.

Jaroslaw Guzinski, Haitham Abu-Rub, and Patryk Strankowski

About the Authors

Jaroslaw Guzinski received M.Sc., Ph.D., and D.Sc. degrees from the Electrical Engineering Department at Technical University of Gdansk, Poland in 1994, 2000, and 2011, respectively. From 2006 to 2009 he was involved in European Commission Project PREMAID Marie Curie, "Predictive Maintenance and Diagnostics of Railway Power Trains," coordinated by Alstom Transport, France. Since 2010, he has been a consultant in the project of integration of renewable energy sources and smart grid for building unique laboratory LINTE^2. In 2012 he was awarded by the Polish Academy of Sciences—Division IV: Engineering Sciences for his monograph *Electric drives with induction motors and inverters output filters—selected problems*. He obtained scholarships in the Socrates/Erasmus program and was granted with three scientific projects supported by the Polish government in the area of sensorless control and diagnostic for drives with LC filters.

He has authored and coauthored more than 120 journal and conference papers. He is an inventor of some solutions for sensorless speed drives with LC filters (three patents). His interests include sensorless control of electrical machines, multiphase drives (five-phase), inverter output filters, renewable energy, and electrical vehicles. Dr Guzinski is a Senior Member of IEEE.

Dr Haitham Abu-Rub holds two PhDs, one in electrical engineering and another in humanities. Since 2006, Abu-Rub has been associated with Texas A&M University–Qatar, where he was promoted to professor. Currently he is the chair of Electrical and Computer Engineering Program there and the managing director of the Smart Grid Center—Extension in Qatar. His main research interests are energy conversion systems, including electric drives, power electronic converters, renewable energy, and smart grid.

Abu-Rub is the recipient of many international awards, such as the American Fulbright Scholarship, the German Alexander von Humboldt Fellowship, the German DAAD Scholarship, and the British Royal Society Scholarship. Abu-Rub has published more than 200 journal and conference papers and has earned and supervised many research projects. Currently he is leading many potential projects on photovoltaic and hybrid renewable power generation systems with different types of converters and on electric drives. He has authored and coauthored several books and book chapters. Abu-Rub is an active IEEE senior member and serves as an editor in many IEEE journals.

Patryk Strankowski received the BSc degree in electrical engineering and the MSc degree in automation systems from the Beuth University of Applied Science, Berlin, Germany in 2012 and 2013, respectively. During his bachelor studies he was involved in the Siemens scholarship program, where he worked for customer solutions at the Department of Automation and Drives.

He is currently working toward his PhD degree at Gdansk University of Technology in Poland. His main research interests include monitoring and diagnosis of electrical drives as well as sensorless control systems and multiphase drives.

Nomenclature

Vectors are denoted with bold letters, for example, $\mathbf{u}_s$.

Latin letters

$a_1, a_2, \ldots a_6$	Coefficients of motor model equations
ABC	Three phase reference frame
C_{s0}	Common mode motor capacitance
d, q	Orthogonal coordinates of rotating reference system with angular speed of rotor flux vector
$\mathbf{e}$	Motor electromotive force
f	Frequency
f_2	Slip frequency
f_{imp}	Inverter modulation frequency
f_n	Nominal frequency
f_{rez}	Resonance frequency
f_r	Rotor rotation frequency
f_s	Stator voltage and current frequency
$\mathbf{i}$	Current
$\mathbf{i}_1$	Inverter output current
$\mathbf{i}_c$	Filter capacitor current
I_n	Nominal current
$\mathbf{i}_s$	Stator current
J	Inertia
K, L	Orthogonal coordinates of rotating reference system with angular speed of stator voltage vector
$k_1, \ldots k_6, k_A, k_B, k_{1L}, k_{2L}$	Observer gain variables
L_σ	Total leakage inductance of motor
$l_{\sigma s}, l_{\sigma r}$	Leakage inductance of stator winding and rotor
L_m	Mutual inductance of stator and rotor

L_{s0}	Motor inductance for common mode
M	Mutual inductance
m_0	Load torque
m_1, m_2	Multiscalar control system variables
m_e	Electromagnetic torque
n	Speed of motor shaft
p	Number of motor pole pairs
Q	Quality factor of resonance circuit
R_0	Circuit resistance of common mode
R_r	Rotor circuit resistance
R_s	Stator circuit resistance
R_{s0}	Motor resistance of common mode
S	Speed direction sign
S_b, S_x	Observer stabilizing magnitude
$t_0, \dots ,t_6$	Sequence switching time of inverter voltage vectors
T_{imp}	Inverter impulse period
t_r	Voltage rise time on motor terminals
T_r	Rotor circuit time constant
T_{Sb}, T_{KT}, T_{Sx}	Inertial filters time constants
$\mathbf{U}$	Voltage
u_α, u_β	Voltage vector components in α, β frame
u_0	Common mode voltage
u_1, u_2	Auxiliary variables of multiscalar control system
U_d	Inverter supply voltage
u_f	Inverter output voltage
u_L	Voltage drop on filter choke
U_n	Nominal voltage
$\mathbf{u}_s$	Stator voltage
u_U, u_V, u_W	Inverter or motor phase voltages U, V, W
UVW	Inverter output phase notation
$\mathbf{U}_{w0}$, $\mathbf{U}_{w1}$, … $\mathbf{U}_{w7}$	Output voltage vector of inverter
w_σ	Coefficient in motor model equations
w_t	Coefficient depending on the pulse width modulator
$\mathbf{x}$	Vector variable of nonlinear object state
x, y	Orthogonal coordinates of rotating reference frame with arbitrary chosen angular speed ω_a
x_{11}, x_{12}, x_{21}, x_{22}	Multiscalar variables
XYZ	Filter output phase description
Z	Impedance
Z_0	Characteristic filter impedance

Greek letters

α, β	Orthogonal coordinates of fixed reference frame
δ	Load angle
δ*	Reference load angle
ξ_d	Damping coefficient

ξ	Disturbance
ρ_{us}	Stator voltage vector position angle in $\alpha\beta$ system
$\rho_{\psi r}$	Rotor linked flux vector position angle
σ	Total coefficient of motor leakage
σ_s, σ_r	Leakage coefficient of stator windings and rotor
τ	Relative time (time in pu)
τ_s'	Time constant of stator circuit
ψ_0	Magnetic flux in the common mode choke core
$\boldsymbol{\psi}_r$	Rotor flux
$\boldsymbol{\psi}_s$	Stator flux
ω_2	Slip pulsation
ω_a	Angular speed of arbitrary chosen reference frame
ω_i	Stator current pulsation
ω_r	Angular speed of motor shaft
ω_u	Stator voltage pulsation
$\omega_{\psi r}$	Rotor flux pulsation

Abbreviations

CM	Common mode
DSPC	Direct speed control
DTC	Direct torque control
EMF	Electromotive force
FFT	Fast Fourier transformation
FOC	Field oriented control
IGBT	Insulated gate bipolar transistor
IM	Induction motor
PE	Earth potential
PI	Proportional–plus–integral controller
PWM	Pulse width modulation
SVM	Space vector modulation
THD	Total harmonic distortion

Contents

1

Introduction to Electric Drives with LC Filters

1.1 Preliminary Remarks

The basic function of electric drives is to convert electrical energy to mechanical form (in motor mode operation) or from mechanical form to electrical energy (in generation mode). The electric drive is a multidisciplinary problem because of the complexity of the contained systems (Figure 1.1).

It is important to convert the energy in a controllable way and with high efficiency and robustness. If we look at the structure of global consumption of electrical energy the significance is plain. In industrialized countries, approximately two thirds of total industrial power demand is consumed by electrical drives [1, 2].

The high performance and high efficiency of electric drives can be obtained only in the case of using controllable variable speed drives with sophisticated control algorithms [3, 4].

In the industry, the widely used adjustable speed electrical drives are systems with an induction motor and voltage inverter (Figure 1.2). Their popularity results mainly from good control properties, good robustness, high efficiency, simple construction, and low cost of the machines [5].

Simple control algorithms for induction motors are based on the *V/f* principle. Because the reference frequency changes, the motor supply voltage has to be changed proportionally. In more sophisticated algorithms, systems such as field-oriented, direct torque, or multiscalar control have to be applied [6, 7]. Simultaneously, because of the estimation possibilities of selected controlled variables, for example, mechanical speed, it is possible to realize a sensorless control principle [7–10]. The sensorless speed drives are beneficial to maintain good robustness. Unfortunately, for sophisticated control methods, knowledge of motor parameters as well as high robustness of the drives against changes in motor parameters is required.

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