PID AND PREDICTIVE CONTROL OF ELECTRICAL DRIVES AND POWER CONVERTERS USING MATLAB®/SIMULINK®

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Liuping Wang, Shan Chai, Dae Yoo, Lu Gan and Ki Ng

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Contents

About the Authors

Liuping Wang received her PhD in 1989 from the University of Sheffield, UK; subsequently, she was an Adjunct Associate Professor in the Department of Chemical Engineering at the University of Toronto, Canada. From 1998 to 2002, she was a Senior Lecturer and Research Coordinator at the Center for Integrated Dynamics and Control, University of Newcastle, Australia before joining RMIT University where she has been Professor of Control Engineering since 2006. She is the author of three books, joint editor of two books, and has published over 180 papers. Liuping Wang has successfully applied PID control and predictive control technologies to many industrial processes. She is a Fellow of Institution of Engineers, Australia.

Shan Chai was born in Shandong, China, in 1981. He received his B.Eng. degree in Electronics Engineering from Shandong University, China in 2004 and his M.Eng. in Electrical Engineering from RMIT University, Australia in 2007. Since 2009 he has been working toward the PhD degree at RMIT that he was awarded in 2013. Dr Shan Chai works in the electrical drives industry.

Dae Yoo received his B.Eng, MSc, and PhD in Electrical Engineering from the RMIT University, Melbourne, Australia in 2003, 2006 and 2013 respectively. From 2006 to 2007, he worked as an embedded software engineer at Orbital Engine Company, WA, Australia, where he was involved in various research oriented automotive projects for developing internal combustion engine control software. During 2008–2009 and since 2012, he has been at the Toyota Technical Center, Melbourne, Australia, where he is a control/software engineer developing advanced control algorithms for motor control units in Toyota’s hybrid system.

Lu Gan, was born in Anhui Province of China, in 1987. He received his B.Eng. degree in Electrical Engineering from RMIT University, Australia, in 2009. Since then he has been working at RMIT towards the PhD degree that he received in 2014. Dr Lu Gan aspires to work in the electrical drives industry.

Ki Ng was born in Hong Kong, in 1986. He received his B.Eng. degree in Electrical Engineering from RMIT University, Australia, in 2009. He is currently working toward a PhD degree at RMIT University, Melbourne, Australia.

Preface

About This Book

Electrical drives play a critical role in electromechanical energy conversions. They are seen everywhere in our daily life from the cooling fans, washing machines to computers. They are the fundamental building blocks in manufacturing, transportation, mineral processing, wind energy and many other industries. For the last several decades, the advances of electronically switched semiconductors in the form of power electronics have made *AC* motor drives gain more prominence over the *DC* machines in industries since they allow a direct connection to power grids via grid connected power converters and have a more reliable physical structure. The grid connected three phase power converter has wide applications in renewable energy generation.

This book gives an introduction to the automatic control of electrical drives and grid connected three phase power converters, and to recent developments in design and implementation. When they are combined together as one unit, it will provide a direct connection for the electrical drives to the power grid for electromechanical energy conversions and renewable wind energy applications. In the context of control system design, electrical drives and grid connected three phase power converters share similar characteristics in their dynamic models and use the same type of semiconductors as actuators in the implementation of control systems. Therefore, in this book, electrical drives and power converters will be studied as individual components of the larger system and examined in the same framework.

As electrical drives and power converters have restricted operations imposed by electronically switched semiconductors, their operational constraints are paramount in the design and implementation of the control systems. In this regard, model predictive control has an established reputation in successfully handling the operational constraints in an optimal manner. Two chapters of this book will be devoted to seeking new predictive control technologies that address the specific needs of controlling electrical drives and power converters, and an additional two chapters will apply the existing predictive control technologies to these systems. Since PID control systems are used in the majority of industrial electrical drives and power converters, understanding these control systems and having the capability to design and implement them are important to a control engineer. There are three chapters in the book that will systematically cover PID control system design, PID control system implementation with anti-windup mechanisms and tuning of PID control systems. All control systems presented in this book have been experimentally validated using self-built test-beds with industrial sized motors. To assist the reader, tutorials about the real-time control system implementation and the physical model based simulators are presented in this book.

This book is intended for readers who have completed or are about to complete four years engineering studies with some basic knowledge in electrical and control systems. The targeted readers are students, practitioners, instructors and researchers who wish to learn electrical motor control and power converter control. The book is self-contained with MATLAB/Simulink tutorials and supported with simulation and experimental results. It is worth mentioning that the material contained in the first five chapters is aimed at readers who are working or are going to work in the relevant engineering field.

Outline of This Book

The structure of the book is illustrated by the block diagram as shown in Figure 0.1. There are ten chapters in this book, covering the topics of mathematical modeling, control of semiconductor switches, PID control system design, implementation and tuning, Finite Control Set (FCS)-predictive control in both $d-q$ and $\alpha-\beta$ reference frames, traditional predictive control in both continuous-time and discrete-time. PID controllers (see Chapters 3–5) are implemented using Pulse-Width-Modulation (PWM) technologies introduced in Chapter 2. The traditional model predictive controllers (see Chapters 8–9) use this technology too. However, FCS-predictive controllers (see Chapters 6–7) are implemented without PWM mechanisms by directly optimizing the switching patterns of semiconductors. Hence, this has significantly simplified the implementation procedure of control systems.

This book begins by discussing the physical models of electrical drives and grid connected three phase power converter since mathematical modeling is the first step toward the design and implementation of control systems. In Chapter 1, the mathematical models of machine drives and power converter are derived in a unified way that firstly uses space vector description of physical variables such as voltage, current and flux, and secondly converts the space vector based model to various reference frames. By adopting this unified framework, it is hoped that through the derivations in a similar process, the dynamic models of drives and power converters can be easily understood by a reader who does not have extensive background in *AC* machines and power converters. It must be emphasized, due to the efforts of generations of electrical engineers (see for example Park (1929), Duesterhoeft *et al*. (1951), Vas (1992), Leonhard (2001), Drury (2009), Hughes and Drury (2013), Quang and Dittrich (2008)), that the dynamics models are highly structured and have incredibly high fidelity, which forms the solid basis for control system designs introduced in the book.

From a control engineer's perspective, the next natural question following from mathematical modeling is how to realize manipulated control variables in applications. It has been well established that control of semiconductor switches is the most efficient and convenient means to achieve control of *AC*

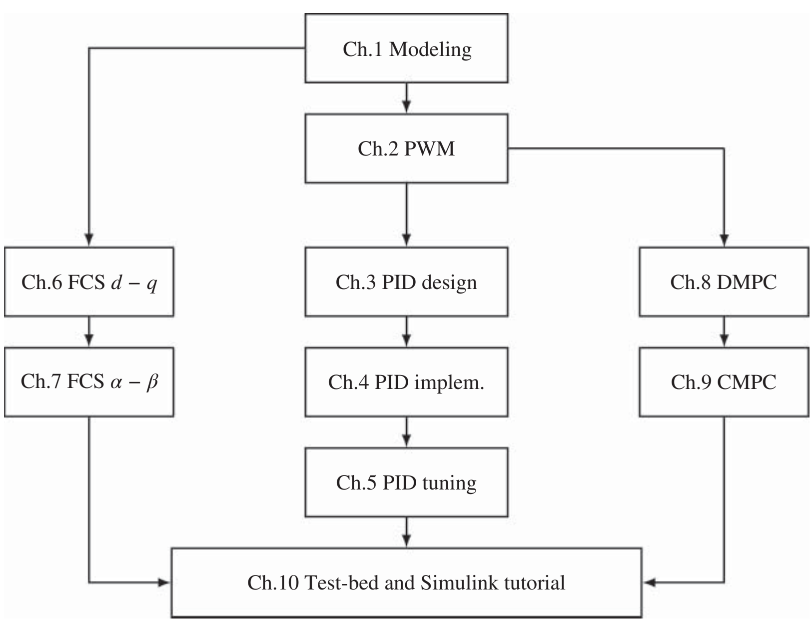

Figure 0.1 Book structure diagram

machine drives and power converters. It is shown in Chapter 2 that they act as actuators in the implementation of control systems where the manipulated control inputs in the form of three phase voltage signals are realized by turning on and off semiconductor switches. Also, the PWM implementation of control systems dictates the operational limits termed linear modulation range, which, in later chapters, will be translated into constraints imposed in the PID and predictive controllers using PWM mechanisms for implementation.

The next three chapters of this book will see the developments of PID control systems for electrical drives and power converter (see Chapters 3–5). In Chapter 3, for *AC* motor control systems, electromechanical torque control is achieved using PI control of currents in the $d - q$ reference frame, followed by achieving further requirements of controlling angular velocity and position via a cascade control system architecture. Identical control strategies are deployed to control the currents of a three phase power converter and its *DC* voltage in a grid connected environment. In all PID controller designs presented in the book, the pole-assignment control method is used. The reasons for this choice of design method is that it is perhaps among the simplest control system design methods and yet offers an effective means of selecting desired closed-loop performance in terms of response to reference signals and to disturbance rejection. In Chapter 4, PI controller implementation is discussed for both current controllers as inner-loop controllers, and velocity and *DC* voltage controllers as outer-loop controllers. In particular, continuous-time controllers are discretized for digital implementation, and operational constraints imposed by PWM operations are taken into consideration in the implementation of PI controllers. In order to avoid integrator wind-up in the presence of control signal reaching saturation limits, anti-windup mechanisms are proposed together with digital implementation, which leads to the so-called velocity form that has naturally embedded anti-windup mechanisms and is convenient for implementation. A MATLAB tutorial is introduced in this chapter to show how an embedded function can be created for the PI controller with its anti-windup mechanism, which has been directly used in the experimental validation. In Chapter 5, sensitivity functions in feedback control systems are introduced to measure the closed-loop control system performance against set-point following, disturbance rejection and noise attenuation in the frequency domain. Current control systems are analyzed for the effects of current sensor errors and harmonics caused by the voltage source inverter used in implementation of the control system. When velocity control, position control or *DC* voltage control is required in a cascade control structure, performance robustness in the outer-loop control system is considered where a weighting function is introduced to quantify the difference between the desired closed-loop performance and the actual closed-loop performance. Parameter variations are also studied using Nyquist plots. A large number of experiments are conducted in this chapter to demonstrate tuning procedures of the PI cascade control systems.

There are two approaches used in this book to generate the gate signal for the semiconductor switches. The first approach uses Pulse Width Modulation (PWM) based on which PID controllers (see Chapters 3–5) and traditional model predictive controllers are implemented (see Chapters 8–9). In control applications, the control signals calculated are the three phase voltage signals that are obtained from one of the controller designs using the model either in the $d - q$ reference frame or $\alpha - \beta$ reference frame. The role of the voltage source inverter with power electronics devices is to realize three phase voltage control signals as closely as possible. Namely, the sinusoidal phase voltage signals created by turning on-off each power switch with PWM technologies are aimed to be closely matched with three phase voltage control signals. The second methodology features a much simpler approach in the implementation of control systems that generates such a gate signal by direct optimization of an error function between the desired control signals and those that can be achieved by semiconductor switches (see Chapters 6–7). In the second approach, there is no need to use the PWM technology; therefore it significantly reduces the complexity of controlling semiconductor switches.

In Chapter 6, in the $d - q$ reference frame, finite control set (FCS) predictive controllers are used to directly optimize inverter states; as a result, PWMs are not required in the implementation of control systems, which simplifies the implementation procedure. The original FCS predictive control systems did not include integrators in their design and implementation. Consequently, there are steady-state errors within control systems. The existence of steady-state errors affects closed-loop performance, particularly when there are parameter uncertainties in the system, which is the main reason why the majority of practical control systems have integrator in the controller structure. By analyzing the original FCS predictive control system without constraints, the discrete-time feedback controller gain and locations of closed-loop eigenvalues are revealed. To embed integrators in the FCS predictive controller, a cascade control system structure is proposed where the inner-loop system is controlled with the original FCS predictive controller and the outer-loop is by an integrated feedback control. There are perhaps many ways to include integrators in the FCS predictive control system; however, the proposed approach has kept the spirit of the original FCS predictive control system and maintained its simplicity both conceptually and computationally. Because the FCS predictive control systems are designed for current control, this chapter will also show how to design velocity and position control for *AC* drives when current controllers are FCS predictive controllers.

In Chapter 7, under investigation is the finite control set (FCS) predictive current control in the $\alpha - \beta$ reference frame (or stationary frame). In the $\alpha - \beta$ reference frame, the currents $i_\alpha(t)$ and $i_\beta(t)$ are linear combinations of three phase currents $i_a(t)$, $i_b(t)$ and $i_c(t)$. Thus, they are sinusoidal functions. So are the voltage variables $v_\alpha(t)$ and $v_\beta(t)$. The current reference signals to FCS predictive control systems are sinusoidal signals, which differentiates current control systems in the $\alpha - \beta$ reference frame from those in the $d - q$ reference frame. It will be shown in this chapter that the original FCS predictive controllers are single-input and single-output controllers in exceptionally simple forms. However, in order to track sinusoidal current reference signals without steady-state errors, a controller with resonant characteristic is required in the $\alpha - \beta$ reference frame. Extensive simulation and experimental results have been presented in these two chapters to show the outstanding closed-loop control performance of FCS predictive control systems.

The next two chapters of this book (see Chapters 8–9) apply the traditional model predictive control algorithms to *AC* machine drives and power converters. These predictive control algorithms were derived for general applications without those restrictions imposed on system dynamics. The MATLAB programs used in applications were given in Wang (2009). Although the traditional predictive control algorithms could be applied to current control, their advantages are perhaps lost to the simpler and more effective FCS predictive control approaches, also to simpler PI controllers. Therefore, in Chapters 8 and 9, velocity control in *AC* drives and *DC* voltage control in power converters are considered, and for these cases, traditional model predictive controllers offer the advantages of designing the control systems using multi-input and multi-output approaches in the presence of constraints.

The final chapter of this book will discuss the test beds used in the experimental evaluations of control systems. For those who wish to know how to perform real-time simulations using the physical models of drives and power converter, Simulink tutorials are given to show the model building process in a step-by-step manner.

References

Drury B 2009 *The Control Techniques Drives and Controls Handbook* 2nd edn. IET.

Duesterhoeft W, Schulz MW and Clarke E 1951 Determination of instantaneous currents and voltages by means of alpha, beta, and zero components. *Transactions of the American Institute of Electrical Engineers* **70**(2), 1248–1255.

Hughes A and Drury B 2013 *Electric Motors and Drives: Fundamentals, Types and Applications* 4th edn. Elsevier.

Leonhard W 2001 *Control of Electrical Drives* 3rd edn. Springer.

Park RH 1929 Two-reaction theory of synchronous machines – part I. *AIEE Transations* **48**(2), 716–739.

Quang NP and Dittrich JA 2008 *Vector Control of Three-Phase AC Machines* 1st edn. Springer.

Vas P 1992 *Electrical Machines and Drives – A Space-Vector Theory Approach*. Oxford University Press, New York, USA.

Wang L 2009 *Model Predictive Control System Design and Implementation Using MATLAB* 1st edn. Springer, London.

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Asking for Feedback

We would like to ask our readers to contact us about any errors or suggestions for future improvement of our book.

Liuping Wang, Shan Chai, Dae Yoo, Lu Gan, Ki Ng
Melbourne, Australia

List of Symbols and Acronyms

Symbols

arg min	Minimizing argument
A	State matrix of state-space model
B	Input-to-state matrix of state-space model
C	State-to-output matrix of state-space model
D	Direct feed-through matrix of state-space model
(A, B, C, D)	State-space realization
ΔU	Parameter vector for the control sequence in discrete time MPC
$\Delta u(k)$	Incremental control at sample k
F_x, Φ	Pair of matrices used in the prediction equation $X = F_x x(k_i) + \Phi \Delta U$
B_v	Viscous friction coefficient in PMSM
f_d	Viscous friction coefficient in induction motor model
$G(s)$	Transfer function model
γ	Tuning parameter for PI controllers
i_α, i_β	Currents of PMSM and power converter in $\alpha - \beta$ reference frame
i_d, i_q	Currents of PMSM and power converter in $d - q$ reference frame
i_{sd}, i_{sq}	Stator currents of induction motor in $d - q$ reference frame
$i_{s\alpha}$, $i_{s\beta}$	Stator currents of induction motor in $\alpha - \beta$ reference frame
$I_{q\times q}$	Identity matrix with appropriate dimensions
J	Performance index for optimization
J_m	Moment of inertia ($\mathrm{kg} \cdot \mathrm{m}^2$)
K_c	Proportional control gain
K_{lqr}	Feedback control gain using LQR
K_{mpc}	Feedback control gain using MPC
K_{fcs}	Feedback control gain using FCS predictive control in $d - q$ reference frame
k^α_{fcs}, k^β_{fcs}	Feedback control gain using FCS predictive control in $\alpha - \beta$ reference frame
K_{ob}	Observer gain vector
$l_i(t)$	The ith continuous-time Laguerre function
$L(t)$	Continuous-time Laguerre functions in vector form
L_s	Inductance of power converter and PMSM
L_r, L_s	Inductance of stator / rotor winding of induction motor
L_h	Machine mutual inductance of induction motor
λ	Lagrange multiplier
$\lambda_i(A)$	The ith eigenvalue of matrix A

λ^l, λ^m, λ^h	Scheduling parameters
μ	Disturbance vector
N	Number of terms used in Laguerre function expansion in continuous time
N_c	Control horizon
N_p	Prediction horizon
Ω_{mpc}, Ψ_{mpc}	Pair of matrices in the cost of predictive control in either the continuous-time or discrete-time design, $J = \eta^T \Omega_{mpc} \eta + 2\eta^T \Psi_{mpc} x(t) + cons$
η	Parameter vector in the Laguerre expansion
p	Scaling factor for continuous-time Laguerre functions
Q, R	Pair of weight matrices in the cost function of predictive control
R_s	Resistance of stator in PMSM and induction motor, also grid resistance in power converter
R_r	Resistance of rotor winding.
$r(\cdot)$	Set-point signal
q^{-i}	Backward shift operator, $q^{-i}[f(k)] = f(k-i)$
$S(s)$	Sensitivity function
$S^i(s)$	Input sensitivity function
S_i	Switching state of inverter
S_d, S_q	Normalized voltage variables of converter's d-axis voltage v_d and q-axis voltage v_q
$T(s)$	Complementary sensitivity function
T_e	Electromagnetic torque ($\mathrm{N \cdot m}$)
T_L	Load torque ($\mathrm{N \cdot m}$)
T_p	Prediction horizon in continuous-time
τ_D	Derivative control time constant
τ_f	Derivative control filter time constant
τ_I	Integral control time constant
θ_r	Mechanical position of motor shaft (radian)
θ_e	Electrical position of motor shaft (radian)
θ_s	Position of synchronous flux (radian)
ψ_s	Stator flux of induction motor (Wb)
ψ_{rd}, ψ_{rq}	Rotor flux of induction motor (Wb)
$u(\cdot)$	Control signal
$u_{s\alpha}$, $u_{s\beta}$	Stator voltages of induction motor (V) in $\alpha - \beta$ reference frame
u_{sd}, u_{sq}	Stator voltages of induction motor (V) in $d - q$ reference frame
v_α, v_β	Voltages of PMSM and power converter (V) in $\alpha - \beta$ reference frame
v_d, v_q	Voltages of PMSM and power converter (V) in $d - q$ reference frame
ω_e	Electrical motor speed (rad/s) (or RPM)
ω_m (or ω_r)	Mechanical motor speed (rad/s) (or RPM)
ω_s	Speed of synchronous flux (rad/s) (or RPM)
ω_g	Grid frequency (rad/s).
ω_{slip}	Slip in induction motor
u^{min}, u^{max}	Minimum and maximum limits for u
w_n	Bandwidth or natural frequency in PI controller design (rad/s)
$x(\cdot)$	State vector
$x(t_i + \tau \mid t_i)$	Predicted state vector at time τ given current state vector $x(t_i)$
$\hat{x}(t)$	Estimated state vector in continuous-time
ξ	Damping coefficient in PI controller design
Y	Predicted output data vector
Z_p	Number of pole pairs

Acronyms

CMPC	Continuous-time model predictive control
DMPC	Discrete-time model predictive control
MMF	Magnetic motive force
PMSM	Permanent magnetic synchronous machine
PLL	Phase-locked loop
PID	Proportional, integral and derivative
FCS	Finite control set
FCS-MPC	Finite control set predictive control
I-FCS-MPC	Integral finite control set predictive control