Advances in Industrial Control

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Alain Glumineau · Jesús de León Morales

Sensorless AC Electric Motor Control

Robust Advanced Design Techniques and Applications

Springer

Alain Glumineau
IRCCyN/Ecole Centrale de Nantes
The University of Nantes Angers Le Mans
Nantes
France

Jesús de León Morales
Facultad de Ingeniería Mecánica y Eléctrica
Universidad Autónoma de Nuevo León
Nuevo León
Mexico

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To my family

Alain Glumineau

To Adeline, Marine and Rafael

Jesús de León Morales

Series Editors' Foreword

The series *Advances in Industrial Control* aims to report and encourage technology transfer in control engineering. The rapid development of control technology has an impact on all areas of the control discipline. New theory, new controllers, actuators, sensors, new industrial processes, computer methods, new applications, new philosophies…, new challenges. Much of this development work resides in industrial reports, feasibility study papers, and the reports of advanced collaborative projects. The series offers an opportunity for researchers to present an extended exposition of such new work in all aspects of industrial control for wider and rapid dissemination.

One of the interesting aspects of editing a control monograph series like *Advances in Industrial Control* is the insight gained as to how control systems theory and control engineering is developing and the interaction between theory and practice. An example is that of nonlinear systems theory, where there are slow but increasing signs of applications using these techniques. We can cite the following monographs from the series to support this thesis:

- *Nonlinear Process Control* by Peter L. Lee (Ed.) (ISBN 978-3-540-19856-7, 1993);
- *Nonlinear* H_2/H_∞ *Constrained Feedback Control* by Murad Abu-Khalaf, Jie Huang and Frank L. Lewis (ISBN 978-1-84628-349-9, 2006);
- *Induction Motor Control Design* by Riccardo Marino, Patrizio Tomei and Cristiano M. Verrelli (ISBN 978-1-84996-283-4, 2010); and
- *Nonlinear Control of Vehicles and Robots* by Béla Lantos and Lőrinc Márton (ISBN 978-1-84996-121-9, 2011).

Nonlinear systems theory is a well-established field of study yet the usual engineering response to system nonlinearity is linearization, multiple models, controller scheduling, and occasional recourse to adaptive and robust control to overcome the uncertainties, and mismatch that the initial linearization approach has introduced. It is therefore interesting to observe some practitioners using existing nonlinear systems theory directly with real-world systems and processes. The most promising application areas are those where there is a well-established historical archive of nonlinear models, suitable for the procedures of nonlinear systems theory. One such field is the control of electrical machines.

The models of electrical machine systems are quite well-defined and have been known for many years. They have a fairly small number of state variables, are nonlinear, and multivariable. Despite small state dimensions, these systems have unmeasurable state variables or states that the engineer wishes to avoid measuring because the appropriate sensors are either costly or difficult and expensive to implement in the physical machine. Add to this model parameters that are uncertain (only approximately known) and/or time-varying, along with the presence of system noise and it is easily seen that the nonlinear control of electrical machines is challenging.

With these difficult characteristics, electrical machines are often used as a benchmark system by academic researchers to test out new control approaches but they also constitute a real-world application field in their own right. Industrially and commercially electrical machines are the essential technological workhorses in the power industries, the utility industries, transport, and many other fields. Such importance makes this *Advances in Industrial Control* monograph *Sensorless AC Electric Motor Control: Robust Advanced Design Techniques and Applications* by Alain Glumineau and Jesús De León Morales a valuable contribution to the series. The authors focus on two issues:

i. AC electrical machine control (permanent magnet synchronous motors, and induction motors); and
ii. the application of nonlinear system techniques.

After revising the models of permanent magnet synchronous motors, and induction motors in Chap. 1, the reader is led through carefully structured chapters that deal with system observability, observer construction, and on to four chapters on control studies that use the observer–controller tandem. The ultimate objective of this work is the sensorless control of AC machines, where the nonlinear observers are used as "soft" sensors for the system controllers. An experimental facility is described in Chap. 1 and this provides experimental validation results for the later control chapters. This is a very instructive addition to the literature of AC motor control and to the *Advances in Industrial Control* monograph series.

Industrial Control Centre, Glasgow, Scotland, UK

Michael J. Grimble
Michael A. Johnson

Preface

Thanks to the technology developments and the recent advances in control theory, it is possible to implement new controllers to a large number of Alternative Current (AC) machines. These controllers are more robust with respect to uncertainties, and more efficient under a wide range of operation conditions in very useful applications. One the most attractive applications of the electrical machines is for transport: vehicle traction that is currently in important development.

The control of AC machines is a challenging problem which has attracted attention thanks to its several applications. For instance, the control problem of the induction motor has recently attracted attention due to its complexity: the induction motor is a nonlinear multi-variable system. Classically, the measurable outputs are the stator currents and voltages. The rotor speed measurement is not always available because of the high costs of sensors, their weakness, or noise sensitivity (the performance at low speed can be poor). Furthermore, the rotor speed is a function of the stator currents and rotor fluxes. The rotor fluxes measurement is not an easy task: it is necessary to introduce sensors in the motor which is expensive and physically complicated to install. When the rotor speed cannot directly be computed from these variables, its control becomes more difficult. On the other hand, the load torque and some parameters like the rotor resistance are usually unknown or inaccurately known and, moreover, time varying. Then, the mathematical models of the AC machines contain parametric uncertainties. Regarding the permanent magnetic synchronous motors, the position and rotor speed knowledge require sensors. However, the introduction of more sensors in the machine implies more complexity and the possibility to introduce failures in the machine. This fact weakens the motor robustness and increases the system cost. The rotor resistance is a time varying parameter depending on the motor temperature. Generally, other parameters (inductance and inertia for instance) are not well known with a sufficient precision. All these elements introduce uncertainties in the model used to design the control, so the control of the machines becomes more complex and its action less efficient.

Clearly, to achieve high-performance objectives, the design of robust controllers requires suitable models describing the dynamical behavior of the machines.

For AC machines, the models are nonlinear and multi-variable (multi-state variables, multi-outputs to track, and multi-control inputs). Moreover, in practice, all the state variables are not measurable, which implies that the implementation of the controller is to be limited. To overcome this difficulty, observation theory provides a solution to reconstruct the unmeasurable state by using observer. Moreover, when the AC machine operates at low speed, some important difficulties appear owing to the loss of the observability property. This property is very important for the estimation of the system state and thus is a preliminary step in the observer design.

Sensorless control of electrical machines implies the new and interesting challenging problem of eliminating the mechanical sensors. The solution to this problem has focused the attention recently in the control community. For this reason, the robust sensorless control of electrical machines is considered as an open problem. To solve this problem, first, it is necessary to study the observability property of these machines. It is well known that the observability of nonlinear systems can depend on the input. In the sensorless case of electrical machines and from the measurement of the inputs (stator voltages) and measured outputs (stator currents), this property could be lost. This situation complicates the reconstruction of the system state. Several concepts and results are introduced in this book as tools to verify if a system is observable or under which conditions it is observable. For that purpose, a precise analysis is necessary for AC machines.

If the system is observable then the design of an observer can begin: it is known that for nonlinear systems there is no general observable form for which an observer can be constructed. Nevertheless, there exist conditions for which a nonlinear system can be exactly transformed into another one so that it is possible to design an observer. The classes of nonlinear system for which an observer can be designed, include: (1) "Luenberger type" (i.e., linear plus a nonlinear output injection), (2) "triangular form" type, or (3) "extended Kalman like" type, like state affine observers or adaptive state affine observers. Furthermore, in terms of convergence, these observers can be divided into two classes: one based on asymptotic methods and the other with finite-time convergence. Recently, the observer design for AC machines is one of the most studied topics in electrical machines research.

The control of the induction motor and synchronous motors have important developments thanks to the advances in power electronics, signal processing, and the progress in computer technology allowing the implementation of sophisticated control strategies. Among the classical control techniques to drive electrical machines, we can find the field-oriented control, or those based on state space representation such as feedback linearization, which have been used in many applications. However, these controllers have shown some limitations in practice.

Recently, the sensorless control problem of AC electrical machines has been intensively addressed and significant contributions have been published to give a solution to this problem. Several observer–controller schemes have been proposed, where conditions are obtained to guarantee the closed-loop stability of the system.

This book presents the basic fundamentals of electrical machines with an emphasis on the permanent magnet synchronous motor and on the induction motor, as well as their mathematical models in different frames and state space representation. After the observability of these AC machines is analyzed, an important contribution is the machines nonlinear observer design. Furthermore, robust control designs based on the backstepping technique and on the sliding mode control are presented. The combination of the observer and controller designs is analyzed and implemented on industrial benchmarks and their results are discussed.

It is clear that the objective of the book is to provide a framework that subsumes significant developments on observer and controller designs for AC electric machines. More precisely, the purpose of the book is to present robust AC machine control designs based on backstepping techniques and sliding mode controls that are combined with nonlinear observers based on either asymptotic or finite-time convergence designs. These observer–controller schemes are evaluated on significant industrial benchmarks with digital simulations and experimental results, showing their performance.

The book is intended to be a reference for practicing engineers, students, and academics, interested in knowing the most recent significant developments on observer design and robust nonlinear sensor or sensorless control techniques applied to AC electrical machines.

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Alain Glumineau
Jesús de León Morales

Contents

Acronyms and Nomenclature

EMF	Electro-Motive Force
IM	Induction Motor
IPMSM	Interior Permanent Magnet Synchronous Motor
PMSM	Permanent Magnet Synchronous Motor
SPMSM	Surface Permanent Magnet Synchronous Motor
$v_s = [v_{sa}, v_{sb}, v_{sc}]^T$	Three-phase stator voltages
$v_r = [v_{ra}, v_{rb}, v_{rc}]^T$	Three-phase rotor voltages
$i_s = [i_{sa}, i_{sb}, i_{sc}]^T$	Three-phase stator currents
$i_r = [i_{ra}, i_{rb}, i_{rc}]^T$	Three-phase rotor currents
$\phi_s = [\phi_{sa}, \phi_{sb}, \phi_{sc}]^T$	Stator fluxes
$\phi_r = [\phi_{ra}, \phi_{rb}, \phi_{rc}]^T$	Rotor fluxes
$v_{s\alpha,\beta} = [v_{s\alpha}, v_{s\beta}]^T$	Two-phase stator voltages in the fixed frame (α, β)
$i_{s\alpha,\beta} = [i_{s\alpha}, i_{s\beta}]^T$	Two-phase stator currents in the fixed frame (α, β)
$v_{r\alpha,\beta} = [v_{r\alpha}, v_{r\beta}]^T$	Two-phase rotor voltages in the fixed frame (α, β)
$i_{r\alpha,\beta} = [i_{r\alpha}, i_{r\beta}]^T$	Two-phase rotor currents in the fixed frame (α, β)
$\phi_{s\alpha,\beta} = [\phi_{s\alpha}, \phi_{s\beta}]^T$	Two-phase stator fluxe in the fixed frame (α, β)
$\phi_{r\alpha,\beta} = [\phi_{r\alpha}, \phi_{r\beta}]^T$	Two-phase rotor fluxes in the fixed frame (α, β)
$v_{sd,q} = [v_{sd}, v_{sq}]^T$	Two-phase stator voltages in the rotating frame (d, q)
$i_{sd,q} = [i_{sd}, i_{sq}]^T$	Two-phase stator currents in the rotating frame (d, q)
$v_{rd,q} = [v_{rd}, v_{rq}]^T$	Two-phase rotor voltages in the rotating frame (d, q)
$i_{rd,q} = [i_{rd}, i_{rq}]^T$	Two-phase rotor currents in the rotating frame (d, q)
$\phi_{sd,q} = [\phi_{sd}, \phi_{sq}]^T$	Two-phase stator fluxes in the rotating frame (d, q)
$\phi_{rd,q} = [\phi_{rd}, \phi_{rq}]^T$	Two-phase rotor fluxes in the rotating frame (d, q)
Φ_r	Rotor magnetic field
$\boldsymbol{\Lambda}$	Inductances matrix
L_{as}, L_{ar}	Self stator and rotor inductances

M_{as}	Two-phase stator mutual inductance
M_{ar}	Two-phase rotor mutual inductance
R_s, R_r	Stator and rotor resistances
$L_s = L_{as} - M_{as}$	Stator cyclic inductance
$L_r = L_{ar} - M_{ar}$	Rotor cyclic inductance
$M_{sr} = \frac{3}{2}M$	Stator and rotor mutual cyclic inductance
$\mathbf{Rs}, \mathbf{Rr}$	Diagonal stator and rotor resistances matrices
$\mathbf{Ls}, \mathbf{Lr}$	Stator and rotor inductances matrices
$\mathbf{Lsr}$	Stator-rotor mutual inductances matrix
J	Motor and Load inertia
f_v	Viscous damping coefficient
f_s	Coulomb friction torque
T_l	Load torque
T_e	Electromagnetic torque
p	Pole pair number
Ω	Rotor mechanical speed
ω	PMSM stator electrical angular frequency
$p\Omega$	Electrical angular frequency associated to the speed $p\Omega$
ω_r	IM rotor electrical angular frequency (or slip pulsation)
$\omega_s = \omega_r + p\Omega$	IM stator electrical angular frequency
$g = \frac{\omega_r}{\omega_s}$	Rotor slip
θ_m	Rotor angular position
θ_e	Electrical position
$\theta_s = \rho$	(d, q) frame angular position
θ_r	Relative angular position of the rotor w.r.t. the (d, q) frame
σ	Blondel leakage coefficient