

# Nonlinear Control of Electric Machines: An Overview

David G. Taylor

**D**ue to the increasing availability of improved power electronics and digital processors at reduced costs, there has been a trend to seek higher performance from electric machine systems through the design of more sophisticated control systems software. There exist significant challenges in the search for improved control system designs, however, since (i) the dynamics of most electric machine systems exhibit significant nonlinearities, (ii) not all state variables are necessarily measured, and (iii) the parameters of the system can vary significantly from their nominal values. In recent years, a wide range of nonlinear methods for feedback control, state estimation, and parameter identification have emerged, and some of these results are reviewed and summarized in this article.

## Introduction

Electric machines are electromechanical energy converters, used for both motor drives and generating systems. Nearly all electric power used throughout the world is generated by so-called synchronous machines (operated as generators), and a large fraction of all this electric power is consumed by so-called induction machines (operated as motors). There are many other types of electric machines, though, distinguished by the materials used, certain key construction features, and the underlying principles of operation.

The first DC machine was constructed by Faraday around 1820, the first practical version was made by Henry in 1829, and the first commercially successful version was introduced in 1837. The three-phase induction machine was invented by Tesla around 1887. Although improved materials and manufacturing methods continue to refine electric machines, it is safe to say that the fundamental issues relating to electromechanical energy conversion have been established for well over a century.

In such an apparently well-established field, it may come as a surprise that today there is more research and development activity related to electric machine systems than ever before. Included in a modern electric machine system is the electric machine itself, power electronic circuits, electrical and/or mechanical sensors, and digital processors equipped with various software algorithms. The recent developments in power semiconductors, digital electronics, and permanent-magnet materials have led to "enabling technology" for today's advanced electric machine systems. But the increasing use of computers, both for

the design of electric machines and for their real-time control, is now contributing more to the level of innovation in electric machine systems than perhaps any other factor.

This article attempts to provide an overview of recent developments in control systems design for electric machines operated as motor drives. The article takes a broad perspective in the sense that the wide variety of different machine types is considered, hopefully from a unifying point of view. On the other hand, in order to limit the scope substantially, an effort was made to focus specifically on the more recent nonlinear control methods, as opposed to the classical methods, which have less potential for achieving high-dynamic performance. An unavoidable limitation of the presentation is a lack of depth and detail in the descriptions of individual achievements; however, the intention was to highlight nonlinear control technology for electric machines to a broad audience, and to guide the interested reader to the appropriate sources for further study.

To put the control design problem into perspective, the article begins with a discussion of electric machine modeling, with emphasis on a generic formulation that can be further specialized to specific machine types as needed. The most commonly made simplifications available for electric machine models are reviewed, and the practical issue of model parameterization is also considered. The next topic addressed is (state-feedback) control design for electric machines and, for purposes of organization, the recent nonlinear methodologies are divided into three groups: exact linearization design, energy shaping design, and backstepping and manifold design. Most, if not all, of the recently reported electric machine control contributions can be roughly placed within these groups. Finally, the roles of parameter identifiers and state observers for electric machine control are briefly discussed.

The list of references included is by no means exhaustive, and is intended only to represent some key publications for each of the topics addressed within the confining structure of this overview article. Although each of the references cited presumably could provide useful background information, two references in particular deserve special mention. The survey/challenge paper [46], dating back to 1986, not only provides clear descriptions of modeling, estimation, and control issues for electric machines that are still relevant today, it also contains an extensive bibliography and would make a helpful supplement to the present article. Also, a very recent special issue of *Proceedings of the IEEE*, [10], contains a collection of informative papers spanning the broad areas of power electronics and motion control.

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# Nonlinear Control Of Electric Machinery

**Zhichao Lian**



## **Nonlinear Control Of Electric Machinery:**

**Nonlinear Control of Electric Machinery** Dawson, 2019-01-22 This work presents nonlinear control algorithms for a benchmark mechanical system actuated by different types of electric machinery emphasizing system stability and robustness pivotal in the development of optimal position trajectory controllers for common motors College or university bookstores may order five or more copies at a special student price available on request from Marcel Dekker *Nonlinear Control of*

*Electric Machinery* D. M. Dawson, Jun Hu, Timothy C. Burg, 1998 *Nonlinear Control of Electric Machines* James Joseph Carroll (Jr), 1994 **Modeling and High Performance Control of Electric Machines** John Chiasson, 2005-05-27

*Modeling and High Performance Control of Electric Machines* introduces you to both the modeling and control of electric machines The direct current DC machine and the alternating current AC machines induction PM synchronous and BLDC are all covered in detail The author emphasizes control techniques used for high performance applications specifically ones that require both rapid and precise control of position speed or torque You ll discover how to derive mathematical models of the machines and how the resulting models can be used to design control algorithms that achieve high performance Graduate students studying power and control as well as practicing engineers in industry will find this a highly readable text on the operation modeling and control of electric machines An Instructor s Manual presenting detailed solutions to all the problems in the book is available from the Wiley editorial department Instructor Support materials are also available Email IAlne@wiley.com **The Control Handbook** William S. Levine, 1996-02-23 This is the biggest most comprehensive and most prestigious

compilation of articles on control systems imaginable Every aspect of control is expertly covered from the mathematical foundations to applications in robot and manipulator control Never before has such a massive amount of authoritative detailed accurate and well organized information been available in a single volume Absolutely everyone working in any aspect of systems and controls must have this book *Nonlinear Control of Electric Machines* James Joseph Carroll, 1993

*Dynamics and Control of Electrical Drives* Wach Piotr, 2011-04-28 Dynamics is a science concerned with movement and changes In the most general approach it relates to life processes as well as behavior in nature in rest It governs small particles technical objects conversion of matter and materials but also concerns people groups of people in their individual and in particular social dimension In dynamics we always have to do with causes or stimuli for motion the rules of reaction or behavior and its result in the form of trajectory of changes This book is devoted to dynamics of a wide class of specific but very important objects such as electromechanical systems This is a very rigorous discipline and has a long tradition as its theoretical bases were formulated in the first half of the XIX century by d'Alembert Lagrange Hamilton Maxwell and other prominent scientists but their crucial results were based on previous pioneering research of others such as Copernicus Galileo Newton This book in its theoretical foundations is based on the principle of least action which governs classical as well as relativistic mechanics and electromagnetism and leads to Lagrange s equations which are applied in the book as

universal method to construct equations of motion of electromechanical systems It gives common and coherent grounds to formulate mathematical models for all lumped parameters electromechanical systems which are vital in our contemporary industry and civilized everyday life From these remarks it seems that the book is general and theoretical but in fact it is a very practical one concerning modern electrical drives in a broad sense including electromechanical energy conversion induction motor drives brushless DC drives with a permanent magnet excitation and switched reluctance machines SRM And of course their control which means shaping of their trajectories of motion using modern tools their designed autonomy in keeping a track according to our programmed expectations The problems presented in the book are widely illustrated by characteristics trajectories dynamic courses all computed by use of developed simulation models throughout the book There are some classical subjects and the history of the discipline is discussed but finally all modern tools and means are presented and applied More detailed descriptions follow in abstracts for the particular chapters The author hopes kind readers will enjoy and profit from reading this book

*Control System Applications* William S. Levine, 2018-10-24 Control technology permeates every aspect of our lives We rely on them to perform a wide variety of tasks without giving much thought to the origins of the technology or how it became such an important part of our lives *Control System Applications* covers the uses of control systems both in the common and in the uncommon areas of our lives From the everyday to the unusual it s all here From process control to human in the loop control this book provides illustrations and examples of how these systems are applied Each chapter contains an introduction to the application a section defining terms and references and a section on further readings that help you understand and use the techniques in your work environment Highly readable and comprehensive *Control System Applications* explores the uses of control systems It illustrates the diversity of control systems and provides examples of how the theory can be applied to specific practical problems It contains information about aspects of control that are not fully captured by the theory such as techniques for protecting against controller failure and the role of cost and complexity in specifying controller designs

**Sensorless AC Electric Motor Control** Alain Glumineau, Jesús de Leon Morales, 2015-03-16 This monograph shows the reader how to avoid the burdens of sensor cost reduced internal physical space and system complexity in the control of AC motors Many applications fields electric vehicles wind and wave energy converters and robotics among them will benefit *Sensorless AC Electric Motor Control* describes the elimination of physical sensors and their replacement with observers i e software sensors Robustness is introduced to overcome problems associated with the unavoidable imperfection of knowledge of machine parameters resistance inertia and so on encountered in real systems The details of a large number of speed and or position sensorless ideas for different types of permanent magnet synchronous motors and induction motors are presented along with several novel observer designs for electrical machines Control strategies are developed using high order sliding mode and quasi continuous sliding mode techniques and two types of observer controller schemes based on backstepping and sliding mode techniques are described Experimental

results validate the performance of these observer and controller configurations with test trajectories of significance in difficult sensorless AC machine problems Control engineers working with AC motors in a variety of industrial environments will find the space and cost saving ideas detailed in Sensorless AC Electric Motor Control of much interest Academic researchers and graduate students from electrical mechanical and control engineering backgrounds will be able to see how advanced theoretical control can be applied in meaningful real systems AC Electric Motors Control Fouad Giri,2013-03-25 The complexity of AC motor control lies in the multivariable and nonlinear nature of AC machine dynamics Recent advancements in control theory now make it possible to deal with long standing problems in AC motors control This text expertly draws on these developments to apply a wide range of model based control design methods to a variety of AC motors Contributions from over thirty top researchers explain how modern control design methods can be used to achieve tight speed regulation optimal energetic efficiency and operation reliability and safety by considering online state variable estimation in the absence of mechanical sensors power factor correction machine flux optimization fault detection and isolation and fault tolerant control Describing the complete control approach both controller and observer designs are demonstrated using advanced nonlinear methods stability and performance are analysed using powerful techniques including implementation considerations using digital computing means Other key features Covers the main types of AC motors including triphase multiphase and doubly fed induction motors wound rotor permanent magnet and interior PM synchronous motors Illustrates the usefulness of the advanced control methods via industrial applications including electric vehicles high speed trains steel mills and more Includes special focus on sensorless nonlinear observers adaptive and robust nonlinear controllers output feedback controllers fault detection and isolation algorithms and fault tolerant controllers This comprehensive volume provides researchers and designers and R D engineers with a single source reference on AC motor system drives in the automotive and transportation industry It will also appeal to advanced students in automatic control electrical power systems mechanical engineering and robotics as well as mechatronic process and applied control system engineers **Nonlinear Control Algorithms for Electric Machines** Praveen Vedagarbha,1997 Vector Control of Three-Phase AC Machines Nguyen Phung Quang,Jörg-Andreas Dittrich,2015-05-14 This book addresses the vector control of three phase AC machines in particular induction motors with squirrel cage rotors IM permanent magnet synchronous motors PMSM and doubly fed induction machines DFIM from a practical design and development perspective The main focus is on the application of IM and PMSM in electrical drive systems where field orientated control has been successfully established in practice It also discusses the use of grid voltage oriented control of DFIMs in wind power plants This second enlarged edition includes new insights into flatness based nonlinear control of IM PMSM and DFIM The book is useful for practitioners as well as development engineers and designers in the area of electrical drives and wind power technology It is a valuable resource for researchers and students Electric Machines and Drives Miroslav Chomat,2011-02-28 The subject of this

book is an important and diverse field of electric machines and drives. The twelve chapters of the book, written by renowned authors both academics and practitioners, cover a large part of the field of electric machines and drives. Various types of electric machines, including three phase and single phase induction machines or doubly fed machines, are addressed. Most of the chapters focus on modern control methods of induction machine drives, such as vector and direct torque control. Among others, the book addresses sensorless control techniques, modulation strategies, parameter identification, artificial intelligence, operation under harsh or failure conditions, and modelling of electric or magnetic quantities in electric machines. Several chapters give an insight into the problem of minimizing losses in electric machines and increasing the overall energy efficiency of electric drives.

Power Converters and AC Electrical Drives with Linear Neural Networks Maurizio Cirrincione, Marcello Pucci, Gianpaolo Vitale, 2017-12-19

The first book of its kind, *Power Converters and AC Electrical Drives with Linear Neural Networks*, systematically explores the application of neural networks in the field of power electronics, with particular emphasis on the sensorless control of AC drives. It presents the classical theory based on space vectors in identification, discusses control of electrical drives and power converters, and examines improvements that can be attained when using linear neural networks. The book integrates power electronics and electrical drives with artificial neural networks (ANN). Organized into four parts, it first deals with voltage source inverters and their control. It then covers AC electrical drive control, focusing on induction and permanent magnet synchronous motor drives. The third part examines theoretical aspects of linear neural networks, particularly the neural EXIN family. The fourth part highlights original applications in electrical drives and power quality, ranging from neural based parameter estimation and sensorless control to distributed generation systems from renewable sources and active power filters. Simulation and experimental results are provided to validate the theories. Written by experts in the field, this state-of-the-art book requires basic knowledge of electrical machines and power electronics, as well as some familiarity with control systems, signal processing, linear algebra, and numerical analysis. Offering multiple paths through the material, the text is suitable for undergraduate and postgraduate students, theoreticians, practicing engineers, and researchers involved in applications of ANNs.

*The Control Handbook (three volume set)* William S. Levine, 2018-10-08

At publication, *The Control Handbook* immediately became the definitive resource that engineers working with modern control systems required. Among its many accolades, that first edition was cited by the AAP as the Best Engineering Handbook of 1996. Now 15 years later, William Levine has once again compiled the most comprehensive and authoritative resource on control engineering. He has fully reorganized the text to reflect the technical advances achieved since the last edition and has expanded its contents to include the multidisciplinary perspective that is making control engineering a critical component in so many fields. Now expanded from one to three volumes, *The Control Handbook*, Second Edition, brilliantly organizes cutting edge contributions from more than 200 leading experts representing every corner of the globe. They cover everything from basic closed loop systems to multi agent adaptive systems and from the control of electric

motors to the control of complex networks Progressively organized the three volume set includes Control System Fundamentals Control System Applications Control System Advanced Methods Any practicing engineer student or researcher working in fields as diverse as electronics aeronautics or biomedicine will find this handbook to be a time saving resource filled with invaluable formulas models methods and innovative thinking In fact any physicist biologist mathematician or researcher in any number of fields developing or improving products and systems will find the answers and ideas they need As with the first edition the new edition not only stands as a record of accomplishment in control engineering but provides researchers with the means to make further advances

**Electromechanical Systems, Electric Machines, and Applied Mechatronics** Sergey Edward Lyshevski, 2018-02-06 Recent trends in engineering show increased emphasis on integrated analysis design and control of advanced electromechanical systems and their scope continues to expand Mechatronics a breakthrough concept has evolved to attack integrate and solve a variety of emerging problems in engineering and there appears to be no end to its application It has become essential for all engineers to understand its basic theoretical standpoints and practical applications Electromechanical Systems Electric Machines and Applied Mechatronics presents a unique combination of traditional engineering topics and the latest technologies integrated to stimulate new advances in the analysis and design of state of the art electromechanical systems With a focus on numerical and analytical methods the author develops the rigorous theory of electromechanical systems and helps build problem solving skills He also stresses simulation as a critical aspect of developing and prototyping advanced systems He uses the MATLAB<sup>TM</sup> environment for his examples and includes a MATLAB<sup>TM</sup> diskette with the book thus providing a solid introduction to this standard engineering tool Readable interesting and accessible Electromechanical Systems Electric Machines and Applied Mechatronics develops a thorough understanding of the integrated perspectives in the design and analysis of electromechanical systems It covers the basic concepts in mechatronics and with numerous worked examples prepares the reader to use the results in engineering practice Readers who master this book will know what they are doing why they are doing it and how to do it

**Self-Driving Vehicles and Enabling Technologies**, 2021-09-22 This book examines the development and technical progress of self driving vehicles in the context of the Vision Zero project from the European Union which aims to eliminate highway system fatalities and serious accidents by 2050 It presents the concept of Autonomous Driving AD and discusses its applications in transportation logistics space agriculture and industrial and home automation

**Energy Efficiency in Electric Devices, Machines and Drives** Gorazd Štumberger, Boštjan Polajžer, 2020-06-18 This Special Issue deals with improvements in the energy efficiency of electric devices machines and drives which are achieved through improvements in the design modelling control and operation of the system Properly sized and placed coils of a welding transformer can reduce the required iron core size and improve the efficiency of the welding system operation New structures of the single phase field excited flux switching machine improve its performance in terms of torque while having higher back EMF and

unbalanced electromagnetic forces A properly designed rotor notch reduces the torque ripple and cogging torque of interior permanent magnet motors for the drive platform of electric vehicles resulting in lower vibrations and noise In the field of modelling the torque estimation of a Halbach array surface permanent magnet motor with a non overlapping winding layout was improved by introducing an analytical two dimensional subdomain model A general method for determining the magnetically nonlinear two axis dynamic models of rotary and linear synchronous reluctance machines and synchronous permanent magnet machines is introduced that considers the effects of slotting mutual interaction between the slots and permanent magnets saturation cross saturation and end effects Advanced modern control solutions such as neural network based model reference adaptive control fuzzy control senseless control torque speed tracking control derived from the 3D non holonomic integrator including drift terms maximum torque per ampere and maximum efficiency characteristics are applied to improve drive performance and overall system operation *New Trends in Technologies* Zhichao Lian,2010-11-02 The grandest accomplishments of engineering took place in the twentieth century The widespread development and distribution of electricity and clean water automobiles and airplanes radio and television spacecraft and lasers antibiotics and medical imaging computers and the Internet are just some of the highlights from a century in which engineering revolutionized and improved virtually every aspect of human life In this book the authors provide a glimpse of new trends in technologies pertaining to devices computers communications and industrial systems **The Mechatronics Handbook - 2 Volume Set** Robert H. Bishop,2002-02-26 Mechatronics has evolved into a way of life in engineering practice and indeed pervades virtually every aspect of the modern world As the synergistic integration of mechanical electrical and computer systems the successful implementation of mechatronic systems requires the integrated expertise of specialists from each of these areas De



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