**Advances in Industrial Control**

**Other titles published in this series:**

*Digital Controller Implementation and Fragility*
Robert S.H. Istepanian and James F. Whidborne (Eds.)

*Optimisation of Industrial Processes at Supervisory Level*
Doris Sáez, Aldo Cipriano and Andrzej W. Ordys

*Robust Control of Diesel Ship Propulsion*
Nikolaos Xiros

*Hydraulic Servo-systems*
Mohieddine Jelali and Andreas Kroll

*Model-based Fault Diagnosis in Dynamic Systems Using Identification Techniques*
Silvio Simani, Cesare Fantuzzi and Ron J. Patton

*Strategies for Feedback Linearisation*
Freddy Garces, Victor M. Becerra, Chandrasekhar Kambhampati and Kevin Warwick

*Robust Autonomous Guidance*
Alberto Isidori, Lorenzo Marconi and Andrea Serrani

*Dynamic Modelling of Gas Turbines*
Gennady G. Kulikov and Haydn A. Thompson (Eds.)

*Control of Fuel Cell Power Systems*
Jay T. Pukrushpan, Anna G. Stefanopoulou and Huei Peng

*Fuzzy Logic, Identification and Predictive Control*
Jairo Espinosa, Joos Vandewalle and Vincent Wertz

*Optimal Real-time Control of Sewer Networks*
Magdalene Marinaki and Markos Papageorgiou

*Process Modelling for Control*
Benoît Codrons

*Computational Intelligence in Time Series Forecasting*
Ajoy K. Palit and Dobrivoje Popovic

*Modelling and Control of Mini-Flying Machines*
Pedro Castillo, Rogelio Lozano and Alejandro Dzul

*Ship Motion Control*
Tristan Perez

*Hard Disk Drive Servo Systems* (2nd Ed.)
Ben M. Chen, Tong H. Lee, Kemao Peng and Venkatakrishnan Venkataramanan

*Measurement, Control, and Communication Using IEEE 1588*
John C. Eidson

*Piezoelectric Transducers for Vibration Control and Damping*
S.O. Reza Moheimani and Andrew J. Fleming

*Manufacturing Systems Control Design*
Stjepan Bogdan, Frank L. Lewis, Zdenko Kovačić and José Mireles Jr.

*Windup in Control*
Peter Hippe

*Nonlinear $H_2/H_\infty$ Constrained Feedback Control*
Murad Abu-Khalaf, Jie Huang and Frank L. Lewis

*Practical Grey-box Process Identification*
Torsten Bohlin

*Control of Traffic Systems in Buildings*
Sandor Markon, Hajime Kita, Hiroshi Kise and Thomas Bartz-Beielstein

*Wind Turbine Control Systems*
Fernando D. Bianchi, Hernán De Battista and Ricardo J. Mantz

*Advanced Fuzzy Logic Technologies in Industrial Applications*
Ying Bai, Hanqi Zhuang and Dali Wang (Eds.)

*Practical PID Control*
Antonio Visioli

*(continued after Index)*

Marco Ariola • Alfredo Pironti

# Magnetic Control of Tokamak Plasmas

Springer

Marco Ariola, PhD
Dipartimento per le Tecnologie
Università degli Studi di Napoli Parthenope
Centro Direzionale di Napoli, Isola C4
80143 Napoli
Italy

Alfredo Pironti, PhD
Dipartimento di Informatica e Sistemistica
Università degli Studi di Napoli Federico II
Via Claudio 21
80125 Napoli
Italy

ISBN 978-1-84800-323-1 e-ISBN 978-1-84800-324-8

DOI 10.1007/978-1-84800-324-8

Advances in Industrial Control series ISSN 1430-9491

British Library Cataloguing in Publication Data
Ariola, M.
Magnetic control of tokamak plasmas. - (Advances in industrial control)
1. Tokamaks 2. Feedback control systems 3. Electromagnetic induction
I. Title II. Pironti, Alfredo
621.4'84
ISBN-13: 9781848003231

Library of Congress Control Number: 2008927412



*Cover design:* eStudio Calamar S.L., Girona, Spain

Printed on acid-free paper

9 8 7 6 5 4 3 2 1

springer.com

# Advances in Industrial Control

Professor Emeritus O.P. Malik
Department of Electrical and Computer Engineering
University of Calgary
2500, University Drive, NW
Calgary
Alberta
T2N 1N4
Canada

Professor K.-F. Man
Electronic Engineering Department
City University of Hong Kong
Tat Chee Avenue
Kowloon
Hong Kong

Professor G. Olsson
Department of Industrial Electrical Engineering and Automation
Lund Institute of Technology
Box 118
S-221 00 Lund
Sweden

Professor A. Ray
Pennsylvania State University
Department of Mechanical Engineering
0329 Reber Building
University Park
PA 16802
USA

Professor D.E. Seborg
Chemical Engineering
3335 Engineering II
University of California Santa Barbara
Santa Barbara
CA 93106
USA

Doctor K.K. Tan
Department of Electrical Engineering
National University of Singapore
4 Engineering Drive 3
Singapore 117576

Professor Ikuo Yamamoto
The University of Kitakyushu
Department of Mechanical Systems and Environmental Engineering
Faculty of Environmental Engineering
1-1, Hibikino,Wakamatsu-ku, Kitakyushu, Fukuoka, 808-0135
Japan

To Angela and to my family (M.A.)

To Teresa and Andrea (A.P.)

# 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.

Internationally, there is much concern about climate change, global warming, and environmental pollution. Two of the major issues are the world's reliance on fossil fuels (coal, oil, and gas) for energy production and the bludgeoning demand for energy as more nations become economically developed and the world becomes increasingly urbanized. If the technological challenges can be overcome, the use of nuclear fusion reactors could provide a sustainable and clean way of meeting the ever-increasing demand for energy in the long term. As evidenced by this monograph, it is inspiring to learn that control engineers are already deeply involved in the international experiments designed to explore the potential of this advanced energy production technology. The tokamak design of nuclear fusion reactor is at the centre of a new research programme, the International Thermonuclear Experimental Reactor (ITER) project and in this *Advances in Industrial Control* monograph, Marco Ariola and Alfredo Pironti explore the problems of tokamak plasma control.

Despite the esoteric technology of tokamak nuclear fusion reactors, there is much that is familiar to the process control or industrial control engineer in this volume; for example, these nuclear fusion reactors have an operational profile that can be divided into the stages of start-up, steady-state and shut-down. The steady-state operational phase is characterized by high-performance control to achieve stable, efficient, and optimized operation whilst meeting the demanding objective of accurate spatial plasma distribution. A key preliminary in any process control project is a study of the process and the authors provide a concise and clear introduction to the basics of plasma physics and models in Part I of the monograph;

this part is supported by two useful appendices on some of the mathematical tools used and the physical units of plasma physics. State-space models, state observers, $H_\infty$ control, and process simulations are some of the familiar techniques used by the authors to meet the demanding spatial control specifications for these processes; however, the research reported in the monograph is more that just simulation studies and proposals for possible future hypothetical controllers, for the authors have worked with some of the world's leading existing tokamak facilities. Chapter 5, 8, and 9 respectively, give practical results of implementations of their control schemes on the FTU Tokamak (Italy), the TCV Tokamak (Switzerland), and the JET Tokamak (United Kingdom). Additionally, the authors present simulation results of their ideas for the control of the new tokamak proposed for the ITER project.

In conclusion, being very aware that most control engineers will not be conversant with the complexities of tokamak nuclear fusion reactor control, the authors have taken special care to give a useful introduction to the background of nuclear fusion, the science of plasma physics and appropriate models in the first part of the monograph (Chapters 1 to 3). This introduction is followed by six chapters (4 to 9) of control studies. In Chapter 4, the generic control problem is established and then five case study chapters follow. These later chapters marry different aspects of the control problem with actual practical results from the different tokamak installations mentioned above. This well structured and staged presentation should make this important and fascinating application accessible to a wide range of readers including process and industrial engineers, academic researchers and postgraduate students in the control and power disciplines.

Industrial Control Centre
Glasgow
Scotland, UK
2008

*M.J. Grimble*
*M.A. Johnson*

# Preface

This book offers a thorough coverage of the magnetic control of a plasma in a tokamak. A plasma is a gas in which an important fraction of the particles is ionized, so that the electrons and ions are separately free; tokamaks are devices constructed in the shape of a torus (or doughnut), in which the plasma is confined by means of magnetic fields. Tokamaks have been proved to be the most promising approach to obtaining energy production from nuclear fusion. For nuclear fusion to happen in a plasma, it is necessary to heat the plasma to a sufficiently high temperature of around 100 million degrees centigrade: this motivates the need for devices in which the plasma is restricted to a finite spatial region without any physical boundary. In a tokamak the confinement is obtained through balancing the expansion pressure in the plasma with the forces exerted by a magnetic field produced by currents flowing in a number of circuits surrounding the plasma. The equilibrium between these forces is such that the plasma assumes the geometrical form of a ring inside the vacuum chamber of the tokamak. The importance of tokamaks for the future of nuclear fusion is demonstrated by the decision to build a new experimental facility, called ITER, as a joint effort by most of the industrialized countries in the world. ITER, whose cost is estimated at about 10 billion euros, will be in operation in 2016, and it is expected to open the way to the commercial exploitation of nuclear fusion.

The magnetic control system is a feedback system, sometimes divided into separate sub-systems, that has the aim of guaranteeing that the plasma equilibrium inside the tokamak is maintained with a prescribed position and shape of the plasma ring. The design of this control system is the main topic of this book. Historically the first problem that was faced was the vertical stabilization of the plasma. Indeed, physical studies demonstrated that the efficiency of the confinement configuration was improved if the plasma exhibited a vertically elongated shape. Unfortunately, with this elongated configuration the equilibrium turned out to be unstable. This problem was tackled using a simple SISO (single-input–single-output) loop, typically with a PID (proportional-integral-derivative) controller whose gains were experimentally tuned. Following this, simple stabilization of the plasma was no longer enough for the experimental activities, and the problem of controlling the overall shape of the plasma gained more and more importance. As a matter of fact, at present, for most tokamak devices there are programmes aimed at improving the performance of the magnetic control systems. This improvement is being achieved with a substantial paradigm shift, from an empirical design approach to a more formal, model-based design approach.

Models deriving from a description of the interaction between the plasma and the circuits are described in terms of a set of nonlinear partial differential equations. The main modelling problem is then that of introducing physical simplifying assumptions and of using approximate numerical methods to obtain a model detailed enough to catch the principal phenomena, but simple enough to make it useful for controller design. Even after these simplifying assumptions, controller design remains a nontrivial problem, mainly for the following reasons:

- the models are typically of high order (more than 100 state variables);
- the model is multi-input–multi-output with a strong coupling between the channels;
- the controller should exhibit stability and performance robustness; indeed it is usually designed on the basis of a nominal plasma equilibrium configuration, but it is expected to perform well during an entire phase of a discharge when some plasma parameters change;
- the control variables are subject to physical limits due to the actuator constraints: voltage, current and power limits should therefore be taken into account in the design phase.

Along with the presentation of various controller schemes, both for plasma vertical stabilization, and for plasma shape, the book gives insight to the basic principles of nuclear fusion and tokamak operation, and a detailed derivation of the linearized model used for the design. In some cases, the controllers described have been implemented on existing tokamaks, and are now in operation. Some of these control schemes can be proposed for use with the experimental tokamak ITER.

The book is divided into two parts: Plasma Modelling and Plasma Control. Then it is organized into nine chapters plus two appendices.

1. *Introduction.* This chapter gives some basic notions about nuclear fusion and plasmas. Then a description of tokamaks and of the main magnetic control problems is given.
2. *Plasma Modelling for Magnetic Control.* In this chapter a description of the plasma model used for the controller design is given. The main simplifying assumptions are illustrated and the steps to derive the model are discussed. An overview of the mathematical tools used in this chapter can be found in the first of the two appendices.
3. *The Plasma Boundary and its Identification.* In this chapter the most common magnetic sensors used in magnetic control are described. Then

the plasma shape identification problem is discussed and an algorithm commonly used to solve this problem is presented.

4. *The Plasma Magnetic Control Problem.* In this chapter the problem of controlling the plasma current, position and shape is discussed. All aspects are covered: the choice of geometrical variables to control; the formulation of the control problem in terms of desired performance and plant limits; the presentation and comparison of the most commonly used control schemes.
5. *Plasma Position and Current Control at FTU.* This chapter describes the design of a current and position controller for the FTU/indexFTU tokamak, a tokamak in operation in Italy. This design is presented as a first example since in this case the problem is made much easier by the fact that the plasma is not vertically unstable.
6. *Plasma Vertical Stabilization.* This chapter focuses on the most basic control problem in a tokamak: the vertical stabilization problem. It is shown how it is possible to separate this problem from the problem of controlling the overall shape, and two solutions are presented.
7. *Plasma Shape Control for ITER.* In this chapter the plasma shape control for the ITER tokamak is discussed. A possible solution is presented; this solution exploits the fact that the vertical position control and the plasma current and shape control can be performed on different time scales.
8. *Plasma Shape Control at TCV.* This chapter presents the design of a high-order multivariable compensator for plasma current, position and shape control in TCV, a tokamak in operation in Switzerland. The problem is formulated in the $H_\infty$ framework.
9. *Plasma Shape Control at JET.* This chapter describes the design of a new plasma shape controller implemented on the JET tokamak, the world's largest tokamak. From a control point of view, the design is a case of optimal output regulation for a non-right invertible plant, *i.e.* for a plant with fewer control inputs than controlled outputs.
10. *Appendices.* The appendices cover some mathematical notions that do not typically belong to the background of control engineers, along with a tutorial describing the various measurement units used in plasma physics.

This work would not have been possible without the help of many people. First of all we have to thank Professor Giuseppe Ambrosino, who initiated us into *automatic control* and introduced us to the problem of plasma control in tokamaks. Without his support and most of all his constant advice, we would never have gained the experience and the knowledge that led us to write this monograph. Thanks, Peppe!

Then we would like to thank Professor Raffaele Albanese, Professor Vincenzo Coccorese, and all the CREATE team: we are really proud to be part of it.

Our sincere gratitude goes to all the people working at the sites where we gained our experience on operating tokamaks. In particular:

- Dr Flavio Crisanti of ENEA of Frascati and all the FTU team for the work done at FTU;
- Dr Jonathan Lister of the CRPP of Lausanne and the TCV team for the work done at TCV;
- Dr Filippo Sartori of UKAEA and the JET team for all the experiments we carried out at JET;
- Dr Alfredo Portone of EFDA, with whom we have been collaborating for more than 15 years on ITER magnetic control.

Finally, we really have to thank our families and loved ones for their support during this task: very often in recent months we have taken time away from them because of this book.

Napoli,
March 2008

*Marco Ariola*
*Alfredo Pironti*

# Contents

## Part II Plasma Control