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_∞ 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.

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