Summary

Magnetic control for nuclear fusion plasmas is one of the main problems to be developed in magnetic confinement devices such as tokamaks. One of the main objectives of using magnetic control in tokamaks is to control the position and shape of the plasma, either to bring the position of the plasma to a given reference or to reject disturbances that may occur and maintain the shape of the plasma at a given pre-defined equilibrium. This is possible by varying the currents and voltages of the poloidal field coils (PF coils in English), by processing the signals generated by the magnetic probes or Mirnov coils in order to reconstruct the of the plasma current centroid position or the last closed magnetic field surface (LCFS in English).

This thesis presents an overview of the control systems and the main control engineering concepts used in the tokamaks as well as the assessments and improvements made for two tokamaks: the JT60-SA (Japan) and the ISTTOK (Portugal). These two devices depend on the active control of the poloidal field coils to control the shape and position of the plasma. The JT60-SA is a superconducting tokamak that is still under construction and will be the largest existing tokamak in the world that will start operations at the end of 2020. The ISTTOK is a tokamak with a large aspect ratio that has been in operation for more than 30 years and is characterised by its alternating current (AC) mode operation and overall flexibility.

The introductory chapter of the thesis allows the reader to understand why a toroidal shape is needed to magnetically confine the plasma, the role of magnetic fields in interaction with the plasma, the way the plasma current is generated, the reasons why a tokamak needs to have poloidal field coils and why they need to have active control in order to stabilize the plasma. The forces experienced by a charged particle in the presence of a toroidal field are also explained until the toroidal force balance expressions are reached. Finally this chapter explains in a simple way how control works in tokamaks and how it has developed over time, and presents to the reader how the thesis is conformed chapter by chapter.

In chapter 2 the plasma control systems are widely described, highlighting the MARTe framework, which will be widely used and referred to in the following chapters, as well as the equilibrium codes used in some tokamaks in order to reconstruct plasma parameters used to achieve the position, shape and plasma current control. The final part of this chapter focuses on the basic concepts of linear and time-invariant systems as well as the design of control systems, which are widely used in the following chapters, such as state-space systems, PID controllers and Kalman filters.

At the beginning of Chapter 3 JT60-SA is described as well as the scenario on which the simulations are based,just like their equilibrium values. Afterwards it is described the CREATE plasma modeling tools and how they establish a system in state-space to describe the plasma around a certain equilibrium. Later, the design of the plasma shape and current controllers is described with two different approaches: using position descriptors called gaps (del inglés para espaciamiento) or magnetic flux surfaces. In the simulations of this chapter two different controllers are used: the controller developed by the QST (Japan National Institutes for Quantum and Radiological Science and Technology) team and the eXtreme Shape Controller (XSC) applied to JT-60SA in the scope of this thesis work, where JT60-SA is simulated through the CREATE model that reconstructs the scenario's equilibrium. This chapter also presents the validation of the method used by QST to reconstruct the last closed magnetic field surface, using a code called CCS by its English name Cauchy Condition Surface. The comparison between these two controllers and the magnetic fluxes obtained using the CREATE model and the CCS code to reconstruct the plasma shape is performed in the presence of different disturbances such as ELMs and with a distinct selection of number of control points for each case. Each controller seems to have its own advantages and disadvantages. In order to test the flexibility of the XSC controller an additional simulation was performed, which consists of changing the plasma shape reference on the top of the tokamak during the simulation with a transfer time from one plasma shape to the other of 1.5 seconds.

Chapter 4 begins with an exhaustive description of ISTTOK: a brief history of the tokamak, diagnostics, actuators and its geometry. Afterwards, the description of the plasma current in ISTTOK and the transitions it has between positive and negative current cycles is deepened. ISTTOK does not lose the ionization of the plasma when the current is practically zero, thus reaching a much longer discharge with AC plasma current. Afterwards it is described the new hardware implementations made by the team of the Institute of Plasmas and Nuclear Fusion (IPFN) which consist of the addition of numerical integrators, which allow the integration of signals from magnetic probes in real time before they are digitized and processed in the MARTe framework. This implementation is fundamental to reconstruct in real time the centroid position of the plasma current. After conditioning the signal in order to remove offsets, an algorithm to subtract the contribution of the plasma current from the integrated measurements of the magnetic probes was implemented through data-driven modelling. In this way it is possible to divide from the measured signals the magnetic contribution of the plasma and the one generated by the poloidal field coils. A multi-filament model is then used to model the plasma from the clean signals of the probes in order to obtain the plasma current centroid position in real time. Multi-filament based models to describe the plasma have been widely used and studied over time. Finally a comparison is made of how with the new implementation of plasma centroid position reconstruction it is possible to have successful transitions between negative and positive plasma currents.

Finally in Chapter 5 the results obtained from new control implementations in real time are shown and analysed. It starts by quickly describing how the implementation of control algorithms interacts with the MARTe framework as well as explaining how the control cycle is closed from the moment the magnetic probe signals are acquired until the current control signals are injected into the poloidal field coils power supplies. Given the actual geometrical and construction characteristics of ISTTOK there are currently few possibilities to have a linear and theoretical model to relate the position of the centroid to the currents in the poloidal field coils. This fact besides being an impediment to develop a Multiple-Input Multiple-Output (MIMO) controller was an incentive to look for other alternatives. In ISTTOK it was chosen to make use of the current computational tools and to use a MIMO model reconstructed from experimental data. From this model it was possible to program in the MARTe framework an optimal controller together with a series of PID controllers, which were tuned empirically. At the end of this chapter a series of plasma discharges in ISTTOK are compared. These results compare the performance of the PID controllers and the MIMO optimal control in terms of plasma centroid position and the amount of current required by the poloidal field coils power supplies.