Design and nonlinear validation of the ITER magnetic control system

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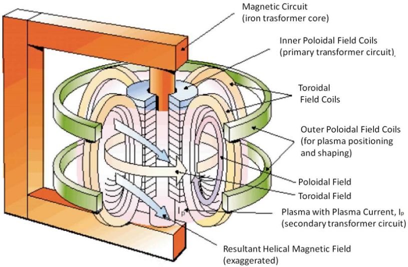
Outline

1. **Introduction**
2. **Proposed architecture for ITER magnetic control**
   - Current decoupling controller
   - Vertical stabilization controller
   - Plasma current controller
   - Plasma shape controller
3. **Nonlinear validation**

Magnetic control in tokamaks



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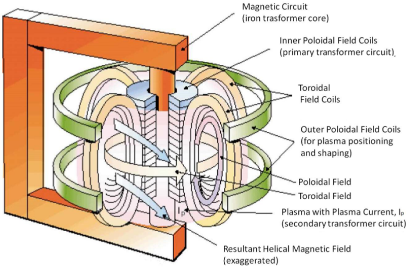

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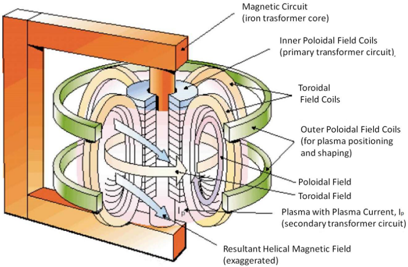

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- In order to obtain good performance, it is necessary to have a plasma with **vertically elongated cross section** ⇒ **vertically unstable plasmas**
- It is important to **maintain adequate plasma-wall clearance during operation**

Limited and diverted plasmas

- The **plasma boundary** is defined as **the largest closed line of the poloidal flux function completely included in vessel** (the boundary of the vacuum vessel region is called the *first wall*)

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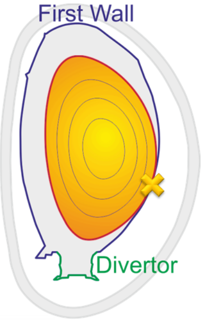
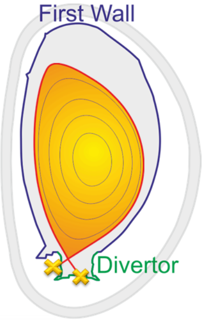
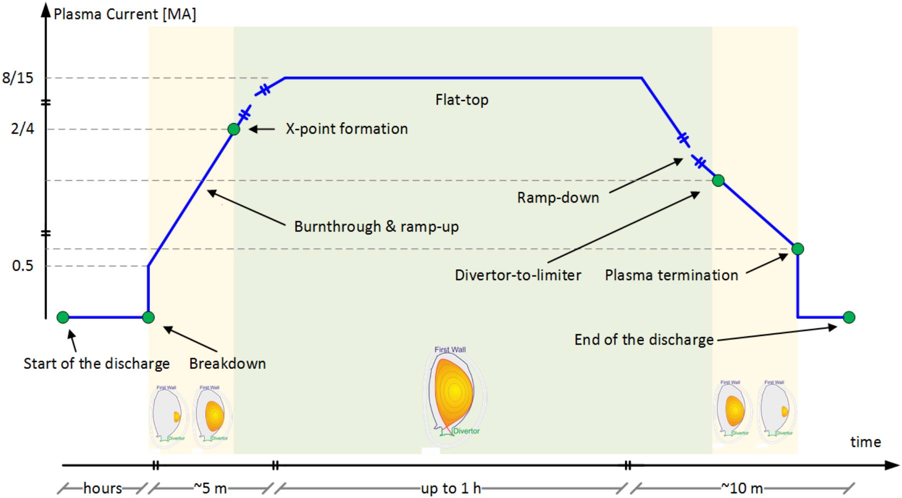
- Two possible cases:
  - the plasma boundary and the first wall have a point in common; this is the case of the so-called **limiter or limited plasmas**
  - the plasma boundary and the first wall do not have any point in common, this is the case of the so-called **divertor or diverted plasmas**. In this case, the plasma boundary is characterized by the **presence of one (or more) X-point**





A tokamak discharge



Motivation and contribution

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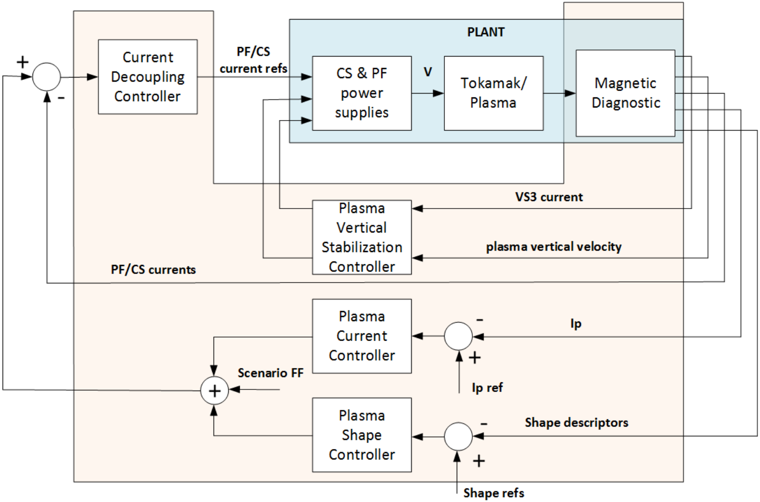
Contribution

- A magnetic control system able to operate the ITER plasma for an entire duration of the discharge, from the initiation to plasma ramp-down

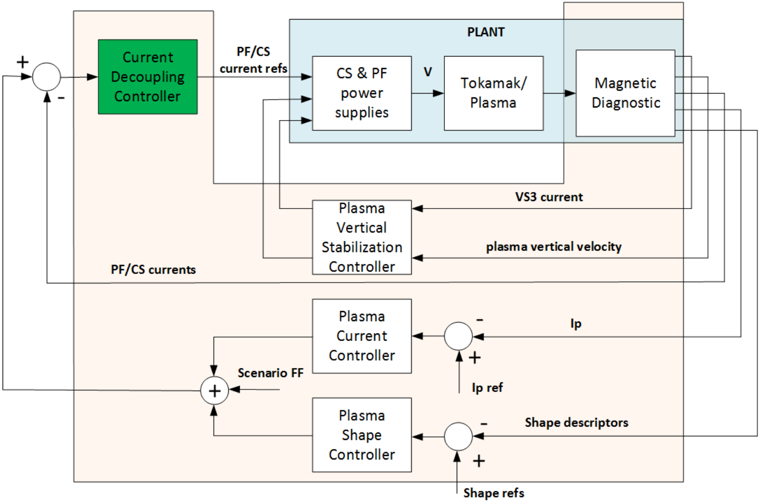
A proposal for the ITER magnetic control system



The proposed architecture

- **Four independent controllers**
    - Current decoupling controller
    - Vertical stabilization controller
    - Plasma current controller
    - Plasma shape controller
- **The parameters of each controller can change on the base of events generated by an external supervisor**
    - **Clock events → time-variant parameters**

Architecture



CS & PF current decoupling controller

- The current decoupling controller receives as input the CS & PF coil currents and their references, and generate in output the voltage references for the power supplies
- **The CS & PF coil current references are generated as a sum of three terms coming from**
  - the **scenario supervisor**, which provides the **feedforwards needed to track the desired scenario**
  - the **plasma current controller**, which generates the **current deviations (with respect to the nominal ones)** needed to compensate errors in the tracking of the plasma current
  - the **plasma shape controller**, which generates the **current deviations (with respect to the nominal ones)** needed to compensate errors in the tracking of the plasma shape

CS & PF current decoupling controller - Control law

Control law

The voltage request computed by the current decoupling controller are

$$V_{PF} = K_c \left(I_{PF,ref} - I_{PF} \right) + R_{PF} I_{IPF}$$

- The the feedback matrix K_c is designed in such a way to assign the desired closed loop system response
- To same behaviour has been assigned to each diagonal term of the closed-loop transfer matrix
- **The design of is based on the vacuum plasmaless model**
- The bandwidth for the tracking of the CS & PF currents is mainly limited by the power supplies voltage limits and by the presence of the passive structures

CS & PF current decoupling controller - Closed-loop transfer functions

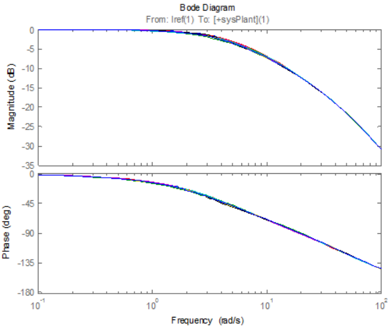


Figure: Bode diagrams of the *diagonal* transfer functions.

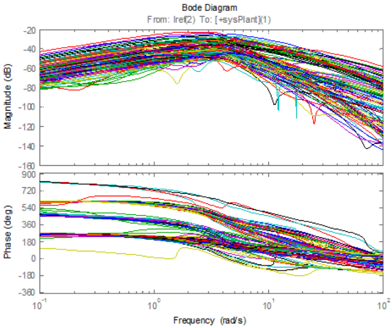
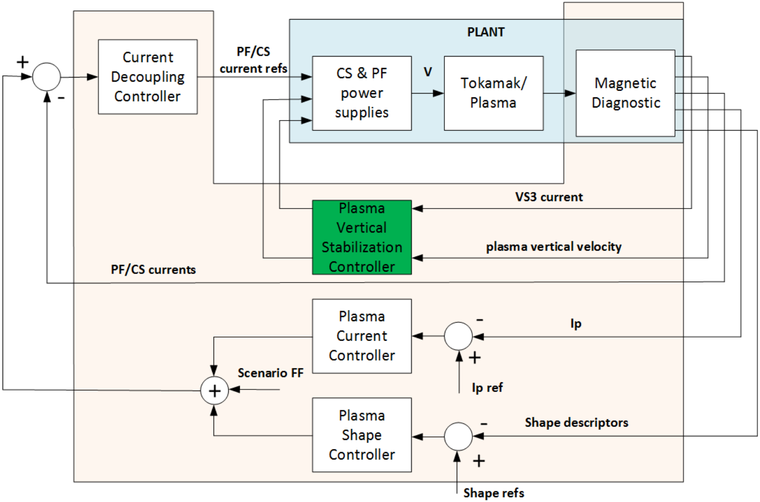


Figure: Bode diagrams of the *off-diagonal* transfer functions.

Architecture



The vertical stabilization controller

- The vertical stabilization controller has as input the centroid vertical velocity, and the current flowing in the *VS*3 circuit (an in-vessel coil set)
- It generates as output the voltage references for the *VS*3 and *VS*1 power supplies (which are the PF outboard coils)

$$\begin{aligned} V_{VS3} &= \mathcal{L}^{-1}\left[F(s)\right] * \left(K_1 \dot{z} + K_2 I_{VS3}\right) \\ V_{VS1} &= K_3 I_{VS3} \end{aligned}$$

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G. Ambrosino et al.
Plasma vertical stabilization in the ITER tokamak via constrained static output feedback
IEEE Trans. Contr. System Tech., 2011

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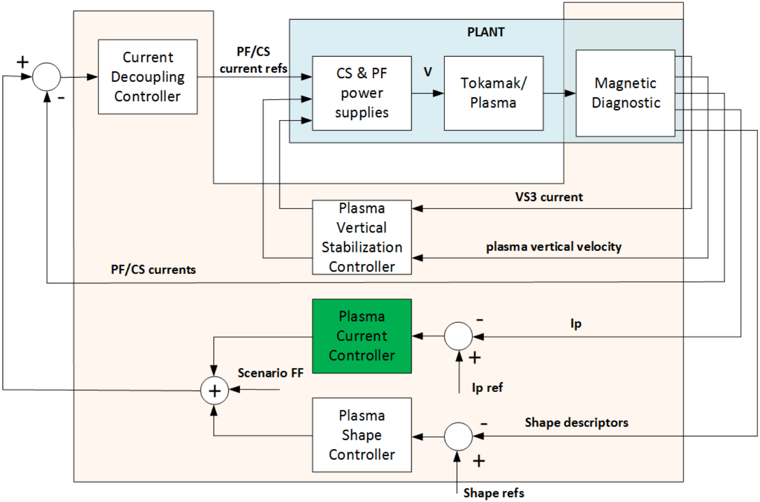
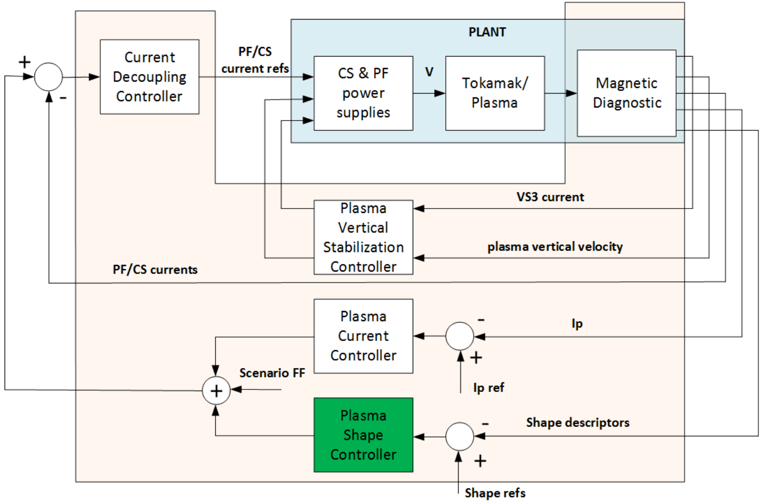


The plasma current controller

- The plasma current controller has as input the plasma current and its time-varying reference, and has as output a set of CS & PF coil current deviations (with respect to the nominal values)
- **The output current deviations are proportional to a set of current providing (in the absence of eddy currents) a transformer field inside the vacuum vessel, so as to reduce the coupling with the plasma shape controller**
- Since it is important, for the plasma current, to track the reference signal during the **ramp-up** and **ramp-down** phases, the controller has been designed with a **double integral action**

The plasma shape controller



Plasma shape descriptors

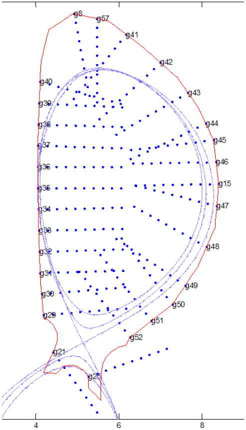


Figure: Control segments.

- Let g_i be the abscissa along i-th control segment ($g_i = 0$ at the first wall)
- Plasma shape control is achieved by imposing

$$g_{i_{ref}} - g_i = 0$$

  on a sufficiently large number of control segments (**gap control**)
- Moreover, if the plasma shape intersect the i-th control segment at g_i, the following equation is satisfied

$$\psi(g_i) = \psi_B$$

  where ψ_B is the flux at the plasma boundary
- Shape control can be achieved also by controlling to 0 the (**isoflux control**)

$$\psi(g_{i_{ref}}) - \psi_B = 0$$

  - $\psi_B = \psi_X$ for *limited-to-diverted* transition
  - $\psi_B = \psi_L$ for *diverted-to-limited* transition

Controlled plasma shape descriptors

- During the limiter phase, the controlled shape parameters are the position of the limiter point, and a set of flux differences (*isoflux control*)
- During the limiter/diverted transition the controlled shape parameters are the position of the X-point, and a set of flux differences (*isoflux control*)
- During the diverted phase the controlled variables are the plasma-wall gap errors (*gap control*)

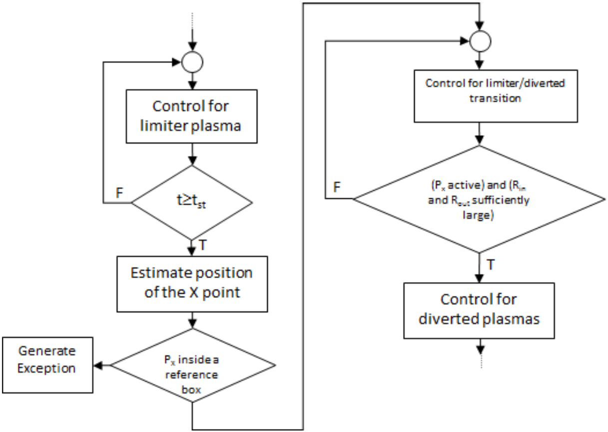
Plasma shape control algorithm

- The plasma shape controller is based on the **eXtreme Shape Controller (XSC) approach**
- The main advantage of the XSC approach is the possibility of tracking a number of shape parameters larger than the number of active coils, minimizing a weighted steady state quadratic tracking error, when the references are constant signals
- The design is based on a plasma linearized state space model

M. Ariola and A. Pironti
Plasma shape control for the JET tokamak - An optimal output regulation approach
IEEE Contr. Sys. Magazine, 2005

G. Ambrosino et al.
Design and implementation of an output regulation controller for the JET tokamak
IEEE Trans. Contr. System Tech., 2008

Plasma shape controller - Switching algorithm



Control for limiter plasma

$t \geq t_{st}$

F

T

Estimate position of the X point

P_x inside a reference box

Generate Exception

Control for limiter/diverted transition

(P_x active) and (R_{in} and R_{out} sufficiently large)

F

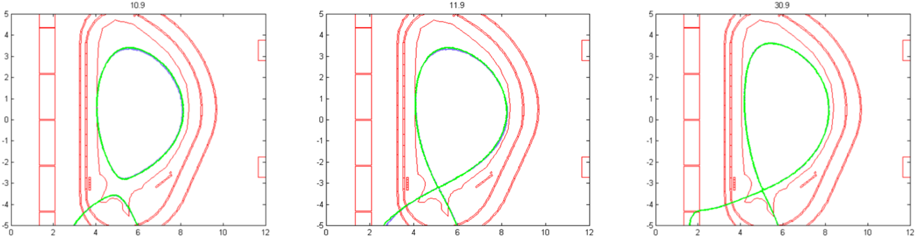
T

Control for diverted plasmas

Limited-to-diverted transition

- Results of nonlinear simulation of the limited-to-diverted configuration during the plasma current ramp-up
- Simulation starts at $t = 9.9\ s$ when $I_p = 3.6\ MA$, and ends at $t = 30.9\ s$ when $I_p = 7.3\ MA$
- The transition from limited to diverted plasma occurs at about $t = 11.39\ s$, and the switching between the isoflux and the gaps controller occurs at $t = 11.9\ s$

Plasma boundary snapshots



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Thank you!