Control of elongated plasmas in superconducting tokamaks in the absence of in-vessel coils

Gianmaria De Tommasi – CREATE/Università di Napoli Federico II – Italy
Email: detommas@unina.it

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Outline

Contributors

The content of this presentation is based on the work made with L. di Grazia, S. Dubbioso, F. Fiorenza, D. Frattolillo, S. Inoue, M. Mattei, A. Pironti and H. Urano, published on *Nucl. Fus.* 2024

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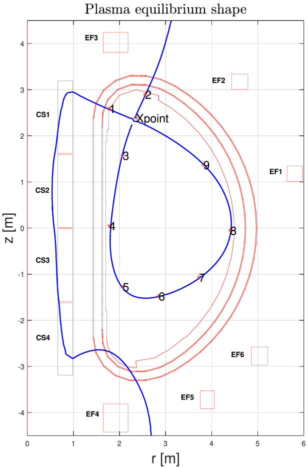


- Commissioning and first operations of superconductive tokamaks like ITER and JT-60SA envisage/have envisaged the possibility to **run discharges with elongated plasmas before the complete installation of the in-vessel components**
- The reference plasmas can be designed with a relatively low growth rate ($\gamma < 1\ s^{-1}$) and can be practically stabilized by the equilibrium control even without a **vertical stabilization (VS) system**
- However, due to
  - model uncertainties
  - disturbances that temporarily *move* the equilibrium far from the reference one
  - *loss* of the passive stabilization of the superconductive coils (when driven in current control mode)

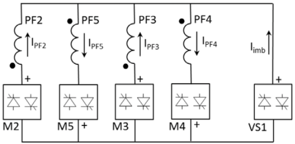
  even slightly elongated *fat* plasmas may practically exhibit a relatively high growth rate ($\gamma \cong 10\ s^{-1}$)
- **Hence, plasma operation would benefit by the presence of an explicit VS system** that shares the superconductive actuators with the other plasma magnetic control tasks

The superconductive PF coils system

- Out-vessel superconductive Poloidal Field (PF) coils are typically less efficient in reacting to fast transients, such as VDEs and HDEs. . .
- . . .however, in absence of in-vessel coils, they should be used also to guarantee plasma vertical stability and react to fast disturbance, e.g. poloidal beta variations that induce fast radial movements. . .
- . . .are shared by the various magnetic control tasks, therefore **effective actuator sharing policies among the various magnetic tasks is necessary**

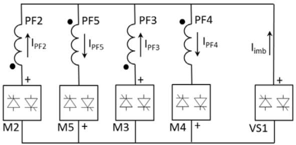
Actuator sharing problem

- The actuator sharing problem is relevant whenever a dedicated VS circuit with the corresponding power supply **are not available**
- **Even when dedicated power supplies are available, coils sharing must be managed** → the so-called **VS1 circuit** at ITER



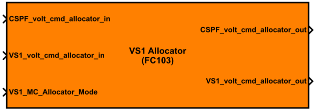
- SC tokamaks envisage the installation of dedicated VS actuators
  - **ITER** → the so-called *VS3* circuit and the corresponding dedicated power supply
  - **JT-60SA** → the *Fast Position Control Coils* (FPCCs) with two dedicated power supplies (upper and lower)
- **Even when dedicated actuator (coils + power supply) are available, effective decoupling between VS and the other magnetic control tasks is necessary (also in the frequency domain)**

Actuator sharing: the ITER VS1 example



At ITER coils PF2-PF5 are shared among

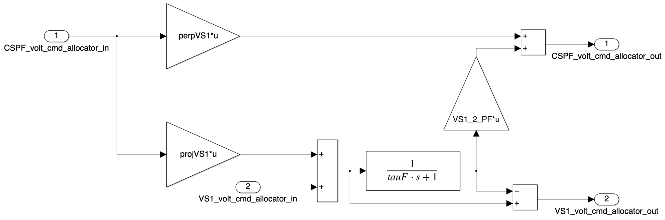
- the plasma current & shape controller, that sends voltage requests to the Main Converters MC2-MC5 **(yet another actuator sharing problem!)**
- the VS system, that sends voltage requests to the VS1 power supply
  - The VS1 requests are *converted* into voltages to be applied to the PF2-PF5 coils, according to the circuit connection $\rightarrow$ the VS system is a multi-input-multi-output (MIMO) control system and the voltage conversion is equivalent to a multiplication by the vector $(0\ 0\ 0\ 0\ 0\ 0\ 1\ 1\ -1\ -1\ 0)$
  - The linear combination of PF2-PF5 voltages can be treated as a **virtual actuator** (in the ITER case with a dedicated power supply)
- The plasma current & shape control requests may have a relevant component along the *VS1 direction*, which would be suppressed by the faster VS1 power supply in absence of a decoupling strategy $\rightarrow$ worsening of the overall magnetic control performance

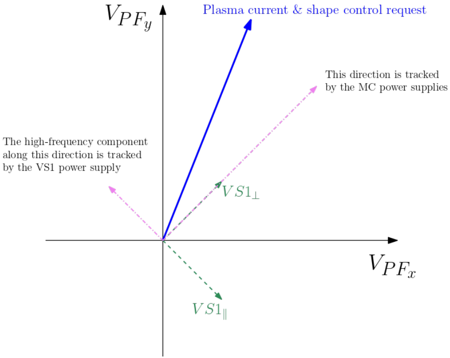


VS1Allocator

- The current architecture of the ITER PCS (for PFPO-1) includes an *allocator* that decouples the VS requests from those ones coming from the plasma current & shape controller
- It performs both geometric and frequency domain decoupling. . .
- . . .and (for those who are interested) is available in PCSSP https://git.iter.org/projects/PCS/repos/pcssp-iter/commits?until=CREATE_modules_GPM_4

The ITER PCS VS1 allocator





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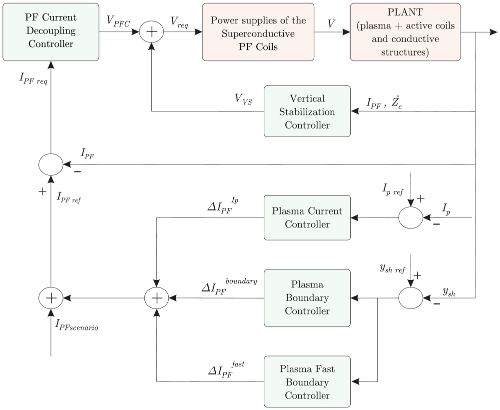
The proposed functional architecture



- The ITER VS1 virtual actuator can rely on a dedicated power supply
- The proposed architecture is **inspired** by the ITER one for PFPO-1 (Mattei *et al.*, *IAEA FEC 2023*), that allows **effective actuator management of CS & PF and decoupling among the plasma current, shape and VS tasks**
- **The ITER control approach can be easily extended to the case of no dedicated power supply and coils for the VS**→ same setup of JT-60SA for integrated commissioning & first operation
- It exploits geometric decoupling in both the PF current and voltage spaces→ the geometric approach requires a **reliable** (control-oriented) **model** to compute the *projection* matrices

The control-oriented plasma-circuit linear model

Starting from a nonlinear lumped parameters model, the following **linearized state-space model** of the plasma-circuit behaviour can be obtained:

$$\delta \dot{\mathbf{x}}(t) = \mathbf{A} \cdot \delta \mathbf{x}(t) + \mathbf{B} \cdot \delta \mathbf{u}(t) + \mathbf{E} \cdot \delta \dot{\mathbf{w}}(t), \quad (1)$$

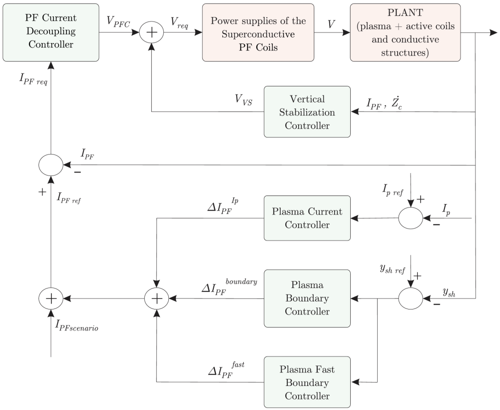
$$\delta \mathbf{y}(t) = \mathbf{C} \cdot \delta \mathbf{I}_{PF}(t) + \mathbf{F} \cdot \delta \mathbf{w}(t), \quad (2)$$

where:

- **A**, **B**, **E**, **C** and **F** are the model matrices
- $\delta \mathbf{x}(t) = \left[\delta \mathbf{I}_{PF}^T(t) \; \delta \mathbf{I}_e^T(t) \; \delta I_p(t)\right]^T$ is the state space vector
- $\delta \mathbf{u}(t) = \left[\delta \mathbf{V}_{PF}^T(t) \; \mathbf{0}^T \; 0\right]^T$ are the input voltages variations
- $\delta \mathbf{w}(t) = \left[\delta \beta_p(t) \; \delta l_i(t)\right]^T$ are the β_p and l_i variations
- $\delta \mathbf{y}(t)$ are the output variations

The model (1)–(2) relates the variations of the PF currents to the variations of the outputs around a given equilibrium

The proposed functional architecture



The architecture includes:

- one inner PF Current (PFC) Controller
- three outer loops, that compute corrections wrt nominal scenario currents (they share the PF currents as *actuators*)
  - Plasma Current Controller
  - Plasma Boundary Controller
  - Plasma Fast Boundary Controller **(to react to fast disturbances)**
- a voltage-driven loop, that acts as VS system and shares (with the PFC Current Controller) the PF voltages as actuators

The PFC controller

- The design of the PFC controller exploits a standard MIMO model-based approach based on the mutual inductance matrix $\widetilde{\mathbf{L}}_{PF}$ in absence of plasma (*plasmaless*)
- The approach is the one adopted at JET (see Sartori *et al.*, *IEEE Contr. Sys. Mag.* 2006) and tested also on EAST (De Tommasi *et al.*, *Fus. Eng. Des.* 2018)

Control law

$$V_{PFC} = \mathbf{K}_{PF} \cdot \left(I_{PF_{ref}} - I_{PF} \right) + \widetilde{\mathbf{R}}_{PF} \cdot I_{PF} \,,$$

where

$$\mathbf{K}_{PF} = \widetilde{\mathbf{L}}_{PF} \cdot \Lambda \,, \quad \Lambda = \begin{pmatrix} 1/\tau_{PF1} & 0 & \dots & 0 \\ 0 & 1/\tau_{PF2} & \dots & 0 \\ \dots & \dots & \dots & \dots \\ 0 & 0 & \dots & 1/\tau_{PF_n} \end{pmatrix}$$

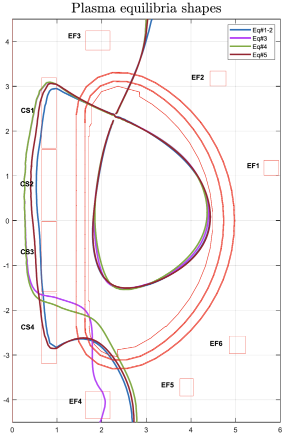
The Λ matrix allows to set the closed-loop time constants of the PF circuits, i.e.

$$\frac{d}{dt} I_{PF} + \Lambda \cdot I_{PF} = \Lambda \cdot I_{PF_{ref}} \,,$$

hence, in closed-loop the PF circuits do not behave as superconductors anymore

How the presence of the PFC controller affects the equilibria stability

"...due to...loss of the passive stabilization of the superconductive coils (when driven in current control mode)...even slightly elongated fat plasmas may practically exhibit a relatively high growth rate..."



JT-60SA equilibria					
	l_i	β_p	κ	A	γ (s^{-1})
Eq#1	0.78	0.14	1.46	2.42	0.36
Eq#2	0.78	0.13	1.47	2.43	1.13
Eq#3	1.16	0.15	1.50	2.52	4.02
Eq#4	1.16	0.15	1.54	2.55	7.64
Eq#5	0.85	0.83	1.45	2.55	Stable

Growth rates comparison			
	γ (s^{-1})	γ_{NC} (s^{-1})	γ_R (s^{-1})
Eq#1	0.36	7.00	6.83
Eq#2	1.13	7.81	7.62
Eq#3	4.02	10.01	9.78
Eq#4	7.64	13.48	13.20
Eq#5	Stable	2.33	2.27

- γ_{NC} is the growth rate obtained by removing from the plasma linear model all the SC coils
- γ_R is the growth rate obtained by considering a resistance of $\sim$ 100 Ω for the PF coils (to emulate the closed-loop time constant due to the presence of the PFC)

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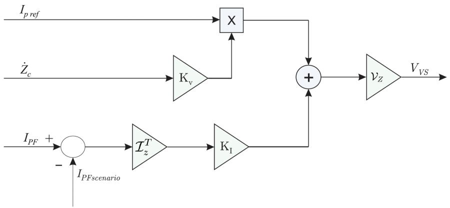
The VS controller



- The output voltages V_{VS} are added to the output voltages VPFC computed by the PFC Controller
- The direction specified by the vector $\mathcal{I}_Z$ is designed (by exploiting the model) to maximizes the radial field able to exert a vertical force on the plasma column
- The linear combination of currents $\mathcal{I}_Z$ can be seen as **virtual circuit** for the VS
- The voltages V_{VS} are chosen to ideally drive the PF currents along the direction given by the vector $\mathcal{I}_Z$ (by distributing the voltages according to $\mathcal{V}_z = -\widetilde{\mathbf{L}}_{PF} \cdot \mathcal{I}_z$)

Two possible way to design the $\mathcal{I}_z$ vector are

- to select two up-down symmetric coils and scale them up by the corresponding number of turns
- to solve a Quadratic Programmin (QP) optimization problem to maximizes the radial field on a grid taking into account additional constraints. Example

$$\min \frac{1}{2} \cdot \delta \mathbf{I}_{PF} \cdot \mathbf{C}_{\widetilde{B}_z}^T \cdot \mathbf{C}_{\widetilde{B}_z} \cdot \delta \mathbf{I}_{PF} \,, \qquad (3)$$

subject to

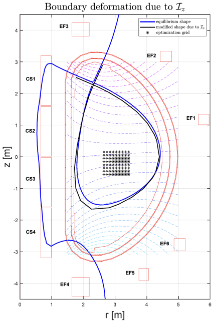
$$\mathbf{C}_{\widetilde{B}_r} \cdot \delta \mathbf{I}_{PF} \geq B_T \cdot \mathbf{1}_{n_{PF}} \,, \qquad (4a)$$

$$\overline{\delta \mathbf{I}}_{PF} \geq \delta \mathbf{I}_{PF} \geq \underline{\delta \mathbf{I}}_{PF} \,, \qquad (4b)$$

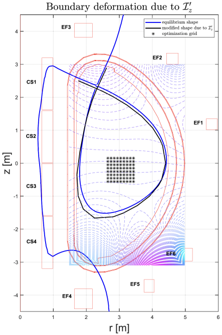
where

- $\mathbf{C}_{\widetilde{B}_z}, \mathbf{C}_{\widetilde{B}_r} \in \mathbb{R}^{m \times n_{PF}}$ are the linear relationship between the PF currents and the vertical $\widetilde{\mathbf{B}}_z$ and radial $\widetilde{\mathbf{B}}_r$ of the poloidal magnetic field on a grid of m points
- $\overline{\delta \mathbf{I}}_{PF}$ and $\underline{\delta \mathbf{I}}_{PF}$ are used to hardly limit the control effort and/or to force some of the PF coils currents to be nonpositive or nonnegative

Possible choices for JT-60SA first operations

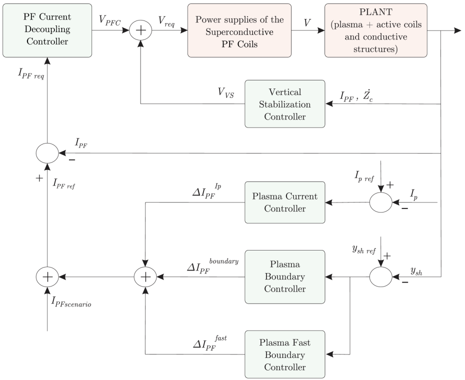


(b)

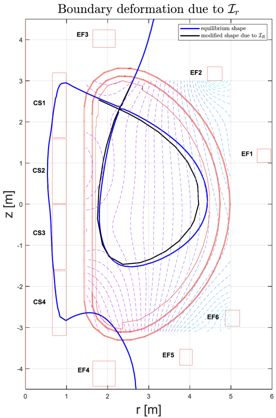


VS virtual circuit	$\widetilde{B}_{r_{\min}}$ (mT)	$\widetilde{B}_{r_{\max}}$ (mT)	$\widetilde{B}_{z_{\min}}$ (mT)	$\widetilde{B}_{z_{\max}}$ (mT)
$\mathcal{I}_z$	4.1	4.7	−0.6	0.4
$\mathcal{I}_z'$	4.1	5.6	−0.1	0.1

- $\mathcal{I}_Z = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0.76 & -0.65 & 0 & 0 \end{pmatrix}^T$ A has been designed selecting two up-down symmetric coils (EF3-EF4)
- $\mathcal{I}_Z' = \begin{pmatrix} 0 & 0 & 0 & 0 & 0.04 & -0.07 & 0.24 & -0.63 & 0.71 & -0.21 \end{pmatrix}^T$ A exploits all the EF coils (without constraining up-down symmetry)



- The **Fast Boundary Controller** is included in the proposed architecture to react to fast plasma shape variations due to external disturbances
- It is designed to induce a specific deformation to balance the one caused by the foreseen disturbance, which depend also on the reference equilibrium
- The Fast Boundary Controller is exploited to promptly counteract the Horizontal Displacement Events (HDE) induced by the switching of the additional heating systems, which in turn correspond to a β_p variation



- The plasma model is exploited to compute a linear combination of PF currents $\mathcal{I}_r \in \mathbb{R}^{n_{PF}}$ (virtual circuit) that induces a plasma deformation capable to counteract the one caused by the envisaged β_p
- Being $\mathbf{C}_{sh} \in \mathbb{R}^{n_{sh} \times n_{PF}}$ the linear relationship between the currents in the PF circuits and the controlled plasma shape descriptors $\mathbf{y}_{sh} \Rightarrow \mathcal{Y}_r = \mathbf{C}_{sh} \cdot \mathcal{I}_r$ is an estimation of the plasma deformation due to $\mathcal{I}_r \rightarrow$ a reliable model is needed!
- $\mathcal{Y}_r$ represents the *direction* in the space of the chosen plasma shape descriptors that is controlled by the linear combination $\mathcal{I}_r$
- $\mathcal{Y}_r$ is chosen to be *as similar as possible* to the mainly outboard deformation induced by β_p variations

The Fast Boundary Control Law

- The couple $(\mathcal{I}_{\mathbf{r}}, \mathcal{Y}_{\mathbf{r}})$ allows to control the plasma along the desired *direction* in the space of the controlled plasma boundary descriptors by means of the Single-Input-Single-Output (SISO) controller

$$\Delta \mathbf{I}_{PF}^{fast}(s) = -\mathcal{I}_{\mathbf{r}} \cdot K_{fast}(s) \cdot \mathcal{Y}_{\mathbf{r}}^{\mathbf{T}} \cdot \mathbf{Y}_{sh}(s)$$

- A possible choice for the dynamic part of the controller $K_{fast}(s)$ is a Proportional Integral (PI) one, i.e.

$$K_{fast}(s) = K_P + \frac{K_I}{s}$$

The Boundary (Shape) Controller

- The **Plasma Shape** control algorithm exploits a MIMO approach based on the Singular Value Decomposition (SVD) of $\mathbf{C}_{sh}$ (*XSC-like* approach, see Ariola & Pironti, IEEE Contr. Sys. Mag. 2005)
- The control law is given by:

$$\Delta \mathbf{I}_{PF}^{boundary}(s) = -K_{boundary}(s) \cdot \mathcal{I}_{\mathbf{z}}^{\perp} \cdot \mathbf{V}_M \cdot \mathbf{S}_M^{-1} \cdot \mathbf{U}_M^T \cdot \mathcal{Y}_{\mathbf{r}}^{\perp} \cdot \mathbf{Y}_{sh}(s)$$

  - $\mathcal{Y}_{\mathbf{r}}^{\perp}$ is a matrix whose columns form an orthonormal basis of $\ker(\mathcal{Y}_r)$
    $\rightarrow$ implies decoupling between the fast and slow boundary control loops
  - $\mathcal{I}_{\mathbf{z}}^{\perp}$ is a matrix whose columns form an orthonormal basis of $\ker(\mathcal{I}_z)$
    $\rightarrow$ implies decoupling with the VS
  - The diagonal transfer matrix $K_{boundary}(s)$ contains a set of n_{PF} regulators needed to improve the dynamic response of the controller

The Plasma Current Controller

- As for the Shape Control, to achieve effective actuator sharing, the output of the **Plasma Current Controller** is projected in the orthogonal subspace of span $[(\mathcal{I}_r, \mathcal{I}_z)]$
- This allows to decouple the I_p control from both the VS and the Fast Boundary Control
- By denoting with $\mathcal{I}^{\perp}$ a matrix whose columns form an orthonormal basis of $\ker\left[\begin{pmatrix}\mathcal{I}_z & \mathcal{I}_r\end{pmatrix}\right]$, the plasma current control law is given by

$$\Delta \mathbf{I}_{PF}^{I_p}(s) = \mathcal{I}^{\perp} \cdot \mathcal{I}_{\mathbf{I_p}} \cdot K_{I_p}(s) \cdot \left(I_{p_{ref}}(s) - I_p(s)\right)$$

- $\mathcal{I}_{\mathbf{I_p}}$ is the linear combination of PF current that provides the so-called *transformer field*

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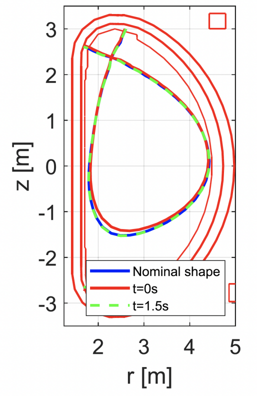
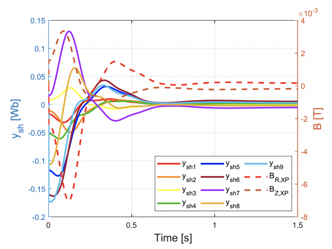
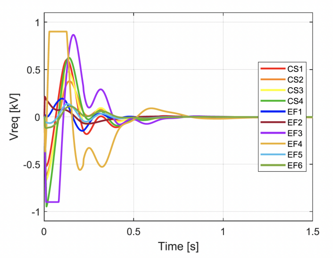
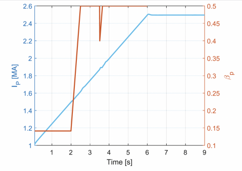
Nonlinear simulation of a 6 cm VDE

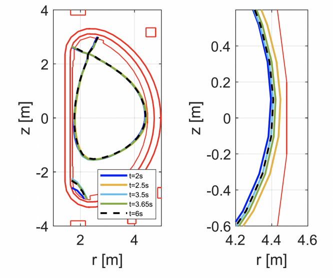


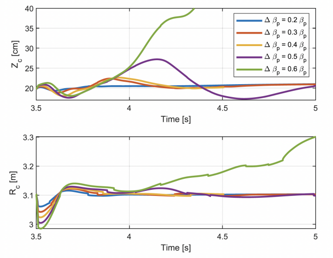




β_p drop during ramp-up







Conclusions

- The proposed **architecture for magnetic control** *explicitly* includes both a VS and Fast Boundary control loop, which are capable to **stabilize the plasma and to counteract fast plasma movement in absence of dedicated in-vessel actuator**
- Sharing of the available superconductive actuators among the various magnetic control tasks is achieved by exploiting a **model-based geometric control design approach** that allows to define **decoupled virtual control circuits**
- Control gains are tuned against the reference scenario $\Rightarrow$ reliable control-oriented (linear) plasma models are necessary for the target equilibria
- The proposed architecture is an **extension** of the one included in the ITER PCS, where the geometric approach is exploited
  - to manage actuator sharing among VS1 and Shape Control
  - to achieve decoupling between plasma shape and I_p control

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