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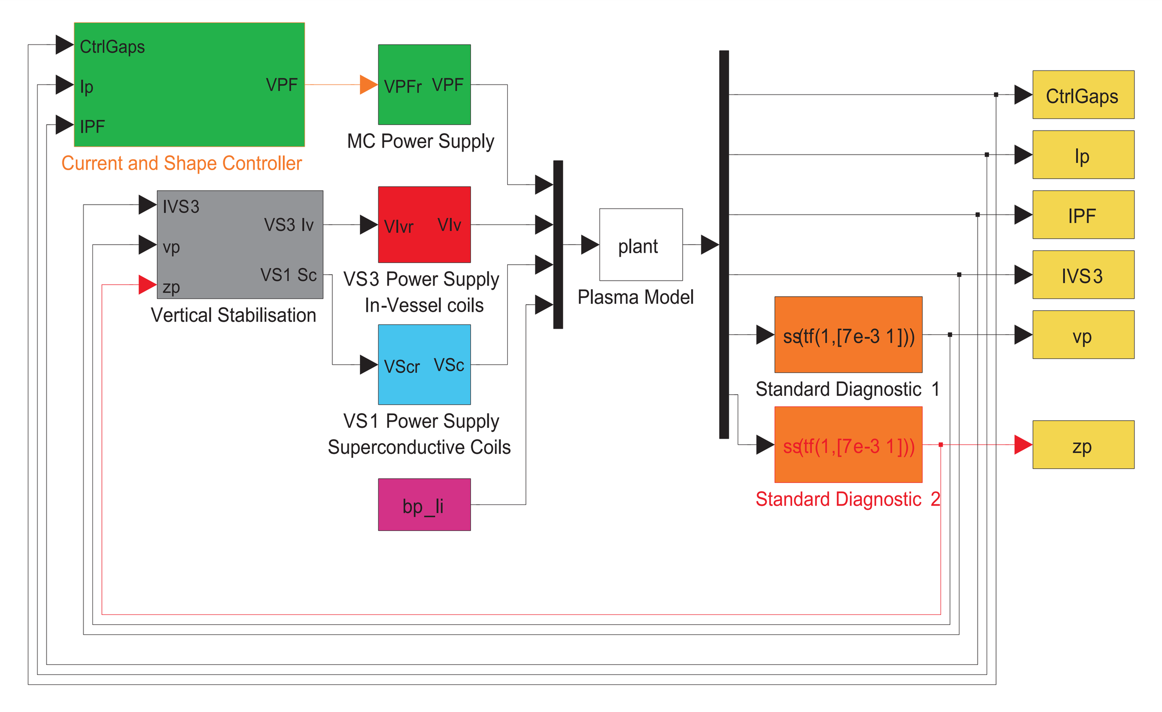
Model predictive control of plasma current and shape for ITER

Overview

- Cascade scheme:
  Inner loop : Vertical Stabilisation (VS)
  Outer loop: plasma Current and Shape Control
- VS: A combination of ohmic in-vessel and superconducting poloidal actuators is used
- VS: ctLQGz (additional control of plasma vertical position z_p with intermediate dynamics)
- CSC: **Model Predictive Control (MPC)**
- Performance assessment and a feasibility study for implementation



Plasma magnetic control scheme with CSC and VS

Plasma models CREATE-L/-NL

High-ordel local linear models from first principles

5 models in different equilibrium points, defined by the nominal I_p, poloidal beta β_p and internal inductance l_i

Simulation of disturbances:

- Vertical displacement event (VDE): via the initial state of the plasma model
- H-L transition: by profiles of β_p and l_i (BPLI) (persistent)

Model code	I_p (MA)	β_p	l_i	Number of states
LMNE	15.0	0.10	1.21	120
LM52	15.0	0.10	0.80	123
LM53	15.0	0.10	1.00	123
LM59	15.0	0.60	0.60	123
LM60	15.0	0.60	0.80	123

Vertical Stabilisation

Actuators:

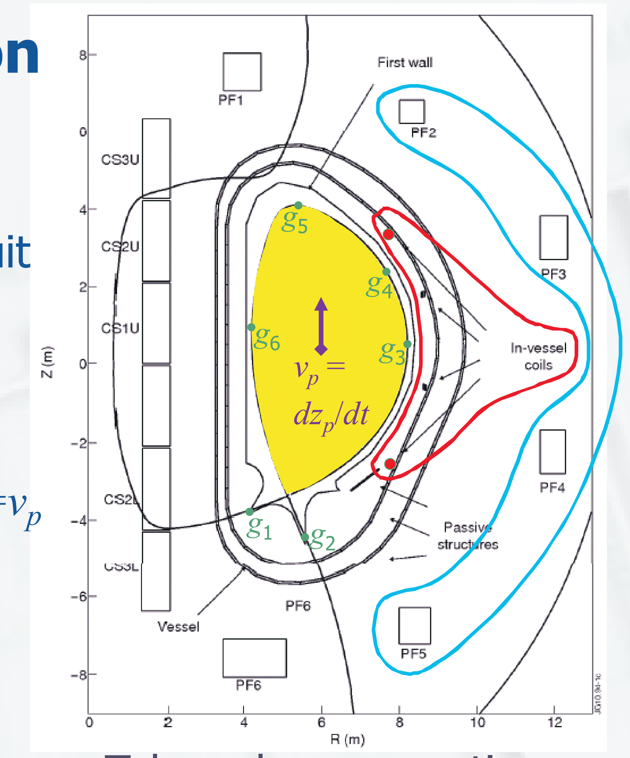
- In-vessel (Ic) coils $u_1 = u_{ic}$
- Superconductive (Sc) circuit VS1 (PF2-5) $u_2 = u_{VS1}$

Controlled outputs:

- Ic coils current $y_1 = x_{ic}$
- Plasma vertical velocity $y_2 = v_p$

Additional ctrl. outputs y_3:

- Plasma vertical position z_p
- Sc circuit current i_{VS1}



Tokamak cross-section

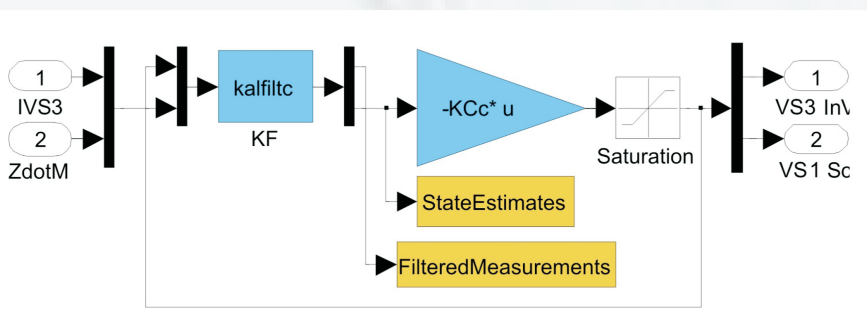
Continuous-time LQG controller (ctLQG)

Linear-quadratic optimal controller with Kalman filter (KF)

State $\mathbf{x}$ not measured; estimated using the KF

Reduced-order model (3)

Saturation block: protection against wind-up



LQG controller block expanded

ctLQGz: ctLQG + additional loop from z_p

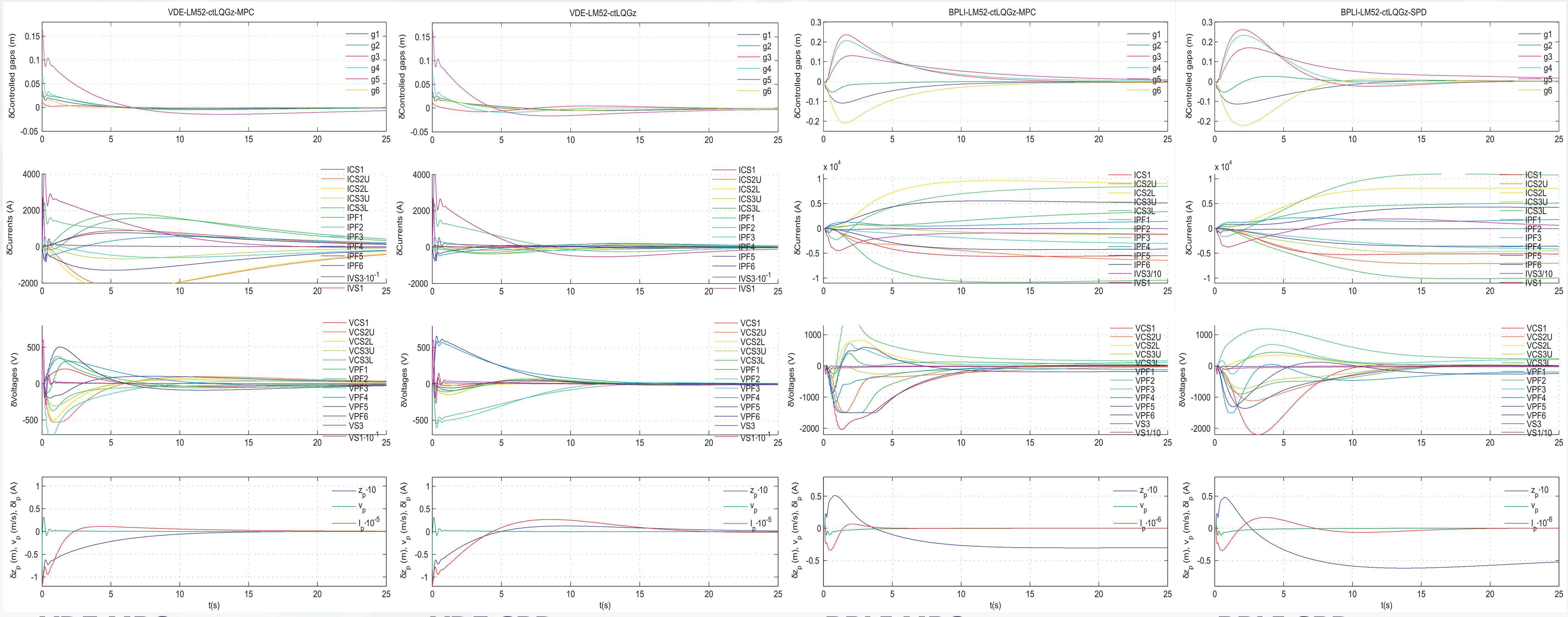
ctLQG only stops z_p from running away after VDE, relies on CSC to bring it back to the origin

ctLQGz returns z_p to the origin faster than the CSC would

Additional loop from $z_p = y_{VS,3}$ to VS1 = $u_{VS,2}$ implemented by augmenting the nominal model with an integrator

$$\mathbf{A}_a = \begin{bmatrix} \mathbf{A}_r & \mathbf{0}_{3\times1} \\ \mathbf{C}_{r,2} & 0 \end{bmatrix}, \quad \mathbf{B}_a = \begin{bmatrix} \mathbf{B}_a \\ \mathbf{0}_{2\times1} \end{bmatrix}, \quad \mathbf{C}_a = \begin{bmatrix} \mathbf{C}_r & \mathbf{0}_{2\times1} \\ \mathbf{0}_{1\times3} & 1 \end{bmatrix} \qquad \mathbf{C}_r = \begin{bmatrix} \mathbf{C}_{r,1} \\ \mathbf{C}_{r,2} \end{bmatrix}$$

Performance comparison: model LM52, VDE and BPLI simulations, ctLQG, MPC vs. SPD



VDE MPC | VDE SPD | BPLI MPC | BPLI SPD

MPC performance with constraints

MPC can consider constraints on control signals (u and y amplitude, u rate...)

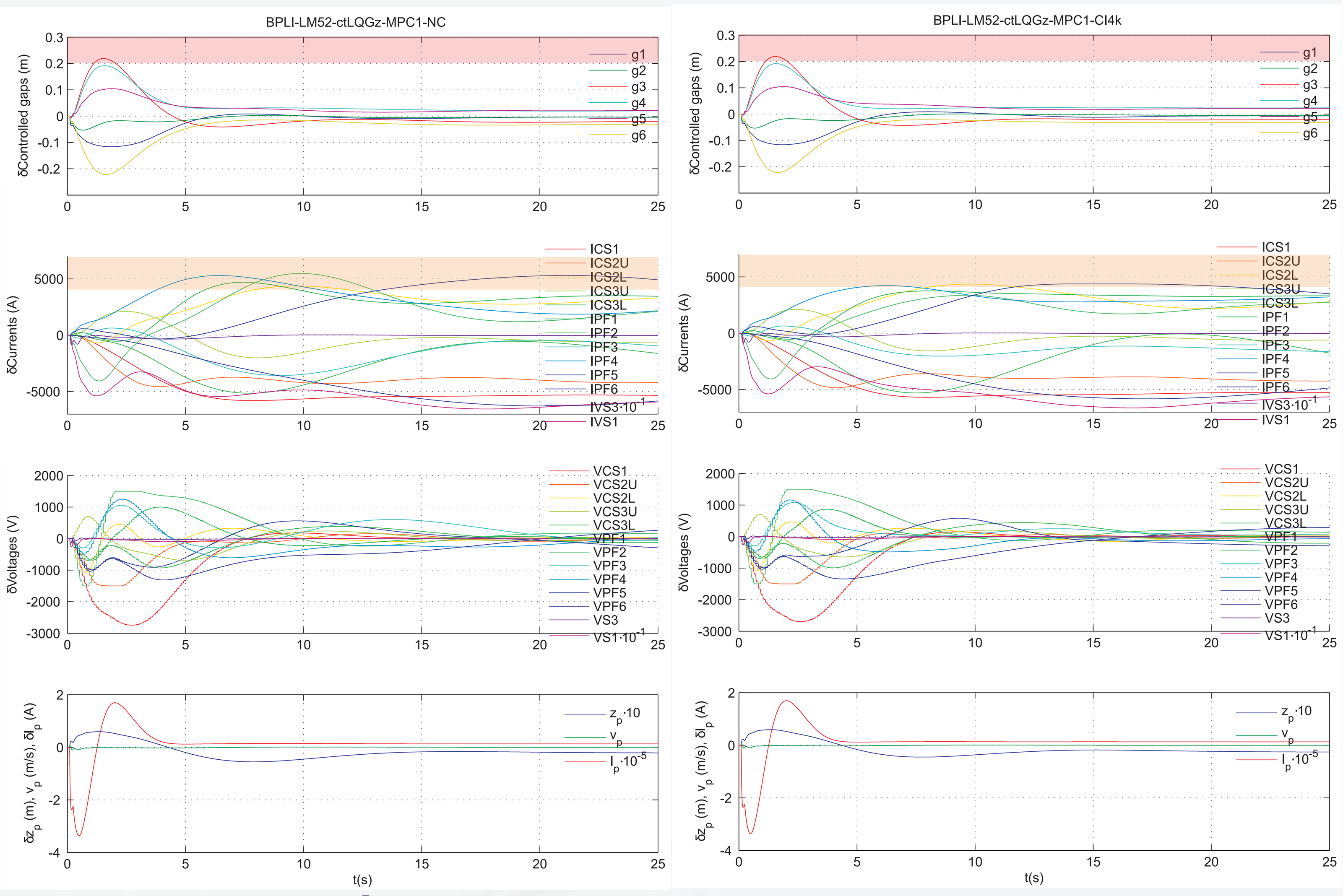
Example:

- $\mathbf{V}_{PF,min} \leq \mathbf{V}_{PF} \leq \mathbf{V}_{PF,max}$, hard constraints
- $\mathbf{I}_{PF} \leq \mathbf{I}_{PF,max}$, soft constraints
- $\mathbf{g} \leq \mathbf{g}_{max}$, soft constraints

Soft constraints are used at the outputs to avoid feasibility issues.

Peak currents are reduced successfully. Small violations remain because the constraints are soft and because of the offset in the $\mathbf{I}_{PF}$ estimate.

The gap peak is not reduced, because this controller is tuned tightly and has no "headroom" to adjust action.



MPC, no constraints | MPC, IPF < 4000 A, g < 0.2 m

Plasma Current and Shape Control

Actuators:

- 11 main power supply voltages $\mathbf{V}_{PF}$

Controlled process outputs:

- Plasma current I_p
- 6 controlled gaps $\mathbf{g}$ (4 gaps and 2 strike points)

Additional process outputs:

- 11 superconductive coil currents $\mathbf{I}_{PF}$

Singular Perturbation Decomposition (SPD), Ariola and Pironti (2003):

A multivariable PI control law from $\mathbf{g}$ and I_p, with an additional P contribution from $\mathbf{I}_{PF}$, with windup protection.

Model Predictive Control

Nominal model LM52 preprocessing:

- Append power-supply and sensor dynamics
- VS prestabilisation
- Extract subsystem $\mathbf{u}_{CSC} = \mathbf{V}_{PF}$ to $\mathbf{y}_{CSC} = [\mathbf{I}_{PF}\ I_{VS3}\ z_p\ I_p\ \mathbf{g}]^T$
- Model reduction (199 to 44 states)
- Conversion to discrete-time (T_s = 0.1 s, ZOH)
- ...Base model $\{\mathbf{A}_{CSC}, \mathbf{B}_{CSC}, \mathbf{C}_{CSC}, \mathbf{0}\}$

Offset-free control of $\mathbf{g}$ and I_p to 0 with integral action, without set-point tracking

- integral action based on disturbance-augmentation with 7 integrators at the control outputs
- velocity-form-augmentation (without tracking) used to prevent offset due to the control cost when the control signal is non-zero at the steady state.

The MPC controller is implemented using modified Multi-Parametric Toolbox (Kvasnica et al., ETH Zürich)

MPC is used in an LQG-like scheme where a Kalman filter estimates the states of the disturbance-augmented model.

Simulation study

Closed-loop performance of the system has been compared with the same ctLQGz VS, using either MPC or SPD for CSC.

Tuning parameters chosen so that reasonable responses are obtained with different local models: LMNE, LM52, LM53, LM59, LM60 with the VDE disturbance, initial amplitude -10 cm and and with the BPLI disturbance (recorded profiles of β_p and l_i, "persistent" disturbance)

Comparing Root-Integral-Square-Error values (from the equilibria), and graphs of signals visually

Conclusions

The feasibility study has shown that efficient simulation performance is achievable using MPC as CSC.

Managing current constraints was demonstrated successfully.

MPC is currently not practically applicable to control problems of this size with sub-second sampling times. However, the implementation may become feasible by using an MPC scheme with a Target Calculator, complexity-reduction approaches and a partly-explicit or FPGA implementation.

Further work is planned regarding tools for tuning support using local linear analysis and for improvements of performance near constraints.