Department of Systems and Control, Jožef Stefan Institute

CREATE PPCC team · COSYLAB · kcstv · Investing in your future · REPUBLIC OF SLOVENIA MINISTRY OF EDUCATION, SCIENCE AND SPORT

The Competence Centre for Advanced Control Technologies is partly financed by the Republic of Slovenia, Ministry of Education, Science and Sport and European Union, European Regional Development Fund

Samo Gerkšič — Jožef Stefan Institute, Ljubljana, Slovenia; Samo.Gerksic@ijs.si

Gianmaria De Tommasi — Associazione EURATOM-ENEA-CREATE, Univ. di Napoli Federico II, Napoli, Italy

Improving magnetic plasma control for ITER

Overview

- A combination of ohmic in-vessel and superconducting poloidal actuators is used
- Cascade scheme:
  Inner loop : vertical stabilisation (VS)
  Outer loop: plasma current and shape control
- Different VS controllers for the inner loop are tested: SOF, LQG
- VS extended with additional control of plasma vertical position z_p with intermediate dynamics
- Faster VS reduces overshoots in gaps after VDE while maintaining robustness

Vertical stabilisation (VS)

Actuators:

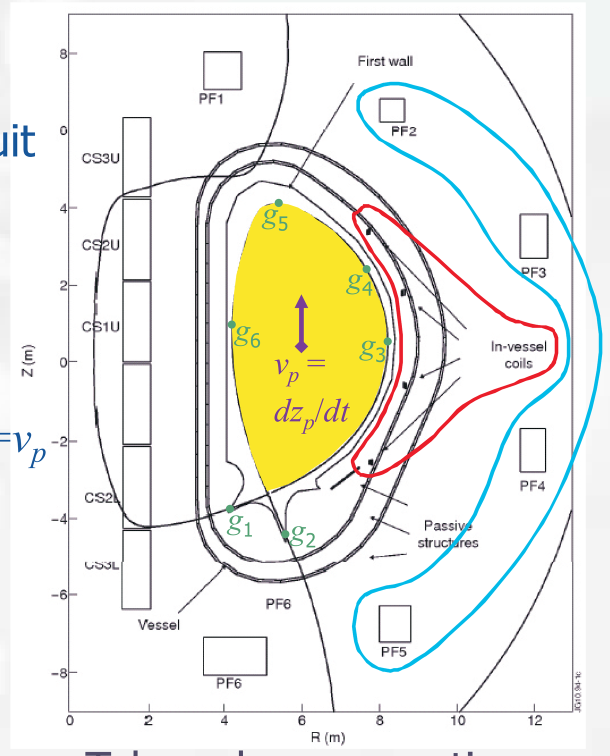
- In-vessel (Ic) coils $u_1 = u_{ic}$
- Superconductive (Sc) circuit VS1 (PF2-5) $u_2 = u_{VS1}$

Controlled outputs:

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

Additional ctrl. outputs y_3:

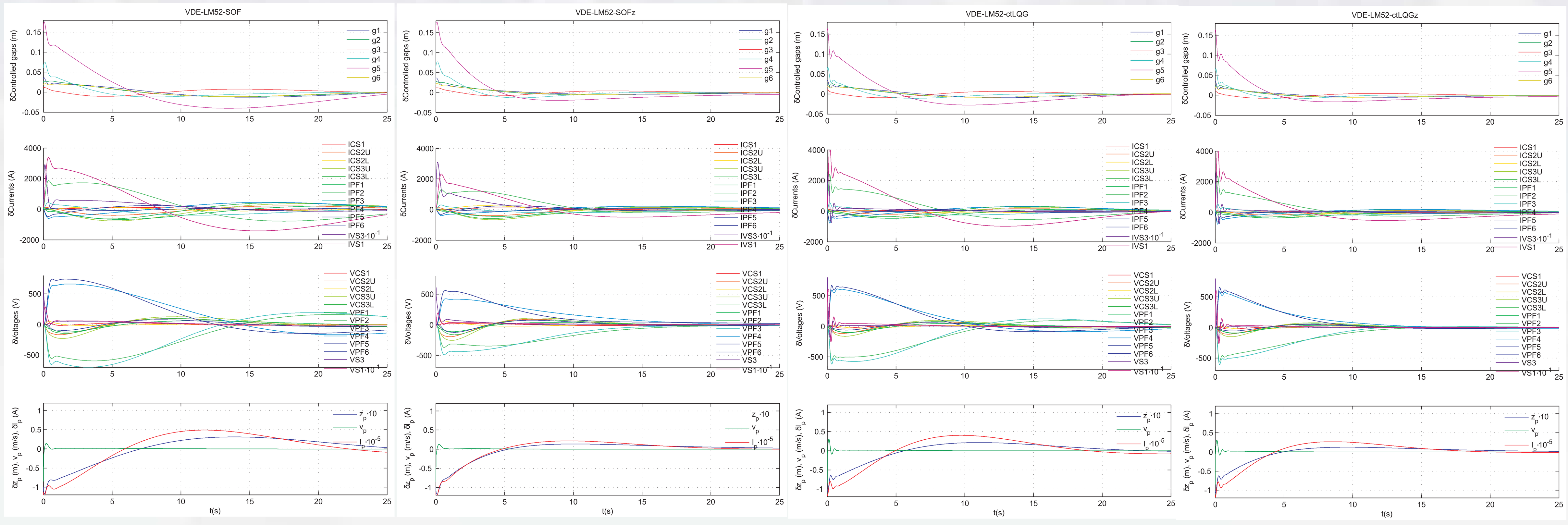
- Plasma vertical position z_p
- Sc circuit current i_{VS1}



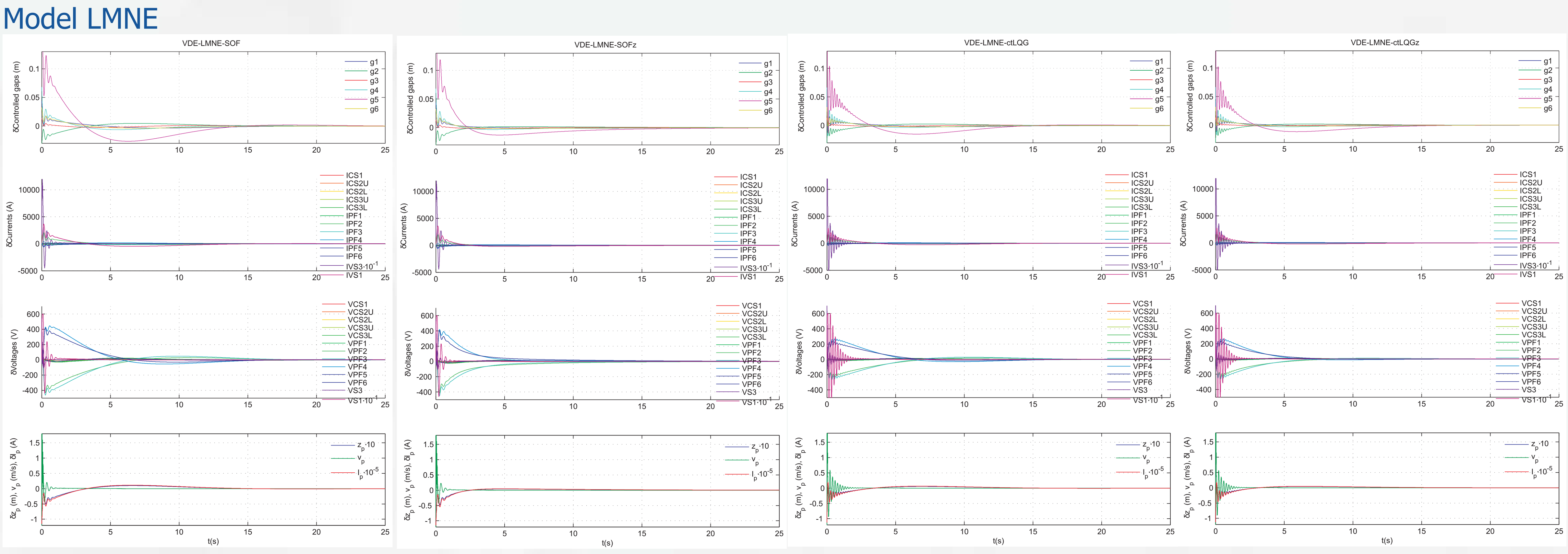
Tokamak cross-section

Performance comparison: 10 cm VDE simulation, same CSC, different VS controllers

Model LM52



Model LMNE



SOF | SOFz | ctLQG | ctLQGz

Plasma current and shape control (CSC)

Actuators:

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

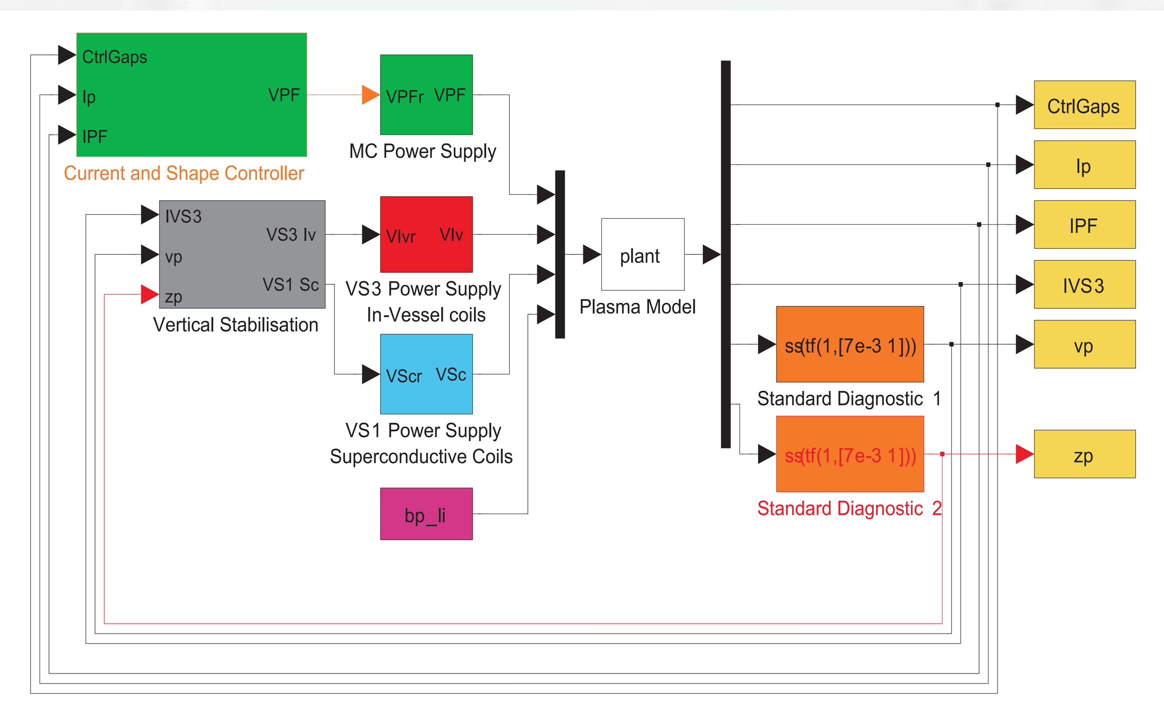
Controlled outputs:

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

Additional measured outputs:

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

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



Plasma magnetic control scheme with CSC and VS

Plasma simulation models CREATE-L/-NL

High-ordel local linear models from first principles

6 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

Model code	I_p (MA)	β_p	l_i	Number of states
LMVS	14.5	0.11	0.85	123
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

Candidate VS controllers

Static Output Feedback (SOF)

Ambrosino et al., 2011

$$\mathbf{u}_{VS}(t) = \mathbf{K}_{SOF}\mathbf{y}_{VS}(t), \quad \mathbf{K}_{SOF} = \begin{bmatrix} 0.0108 & -1200 \\ 0.1 & 0 \end{bmatrix}$$

Parameters tuned for the most problematic model LMNE

SOFz: SOF + additional loop from z_p

Additonal gain from $z_p = y_{VS,3}$ to VS1 $= u_{VS,2}$

$$\mathbf{u}_{VS}(t) = \mathbf{K}_{SOFz}\mathbf{y}_{VS}(t), \quad \mathbf{K}_{SOFz} = \begin{bmatrix} 0.0108 & -1200 & 0 \\ 0.1 & 0 & -10000 \end{bmatrix}$$

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

SOFz brings z_p back to the origin faster than the CSC would

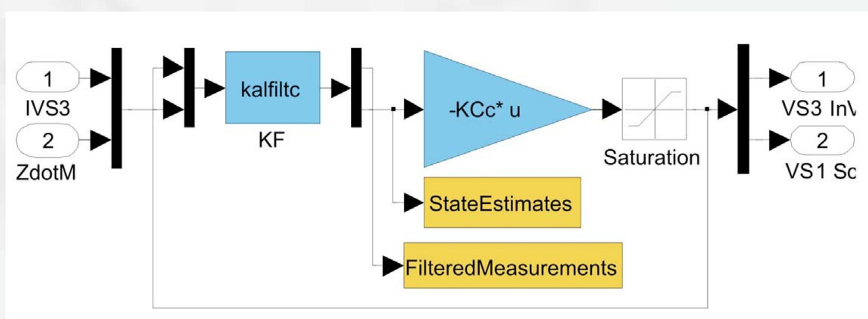
Continuous-time LQG controller (ctLQG)

Linear-quadratic optimal controller with Kalman filter (KF)

Reduced-order model to avoid "over-fitting" to particular local dynamics: Schur balanced truncation (schurmr)

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

Saturation block: protection against wind-up



LQG controller block expanded

ctLQG tuning:
  nominal model + LQ cost matrices + KF covariance matrices

LQG may be sensitive to modelling error...
  tuning based on Loop Transfer Recovery

Graphical tuning environment based on linear analysis tools

Nominal model $\{\mathbf{A}_r, \mathbf{B}_r, \mathbf{C}_r, \mathbf{0}\}$:
  model LMVS, 3rd-order reduced model, schurmr

$$\mathbf{Q}_\mathbf{y} = \begin{bmatrix} 0.00001 & 0 \\ 0 & 1 \end{bmatrix}, \quad \mathbf{R}_\mathbf{u} = \begin{bmatrix} 0.008 & 0 \\ 0 & 0.0001 \end{bmatrix}$$

$$\mathbf{Q}_{KF,\mathbf{y}} = \mathbf{B}_r\mathbf{B}_r^T, \quad \mathbf{R}_{KF,\mathbf{u}} = \begin{bmatrix} 0.001 & 0 \\ 0 & 10^{-13} \end{bmatrix}$$

ctLQGz: ctLQG+additional loop from z_p

The additional loop from z_p to VS1 implemented by augmenting the nominal model with an integrator

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

Additional tuning parameters:

$$\mathbf{Q}_{\mathbf{y}a} = \begin{bmatrix} \mathbf{Q}_{\mathbf{y}a} & \mathbf{0} \\ \mathbf{0} & 2\cdot10^2 \end{bmatrix}, \quad \mathbf{Q}_{KF,\mathbf{y}a} = \begin{bmatrix} \mathbf{B}_r\mathbf{B}_r^T & \mathbf{0} \\ \mathbf{0} & 1 \end{bmatrix}, \quad \mathbf{R}_{KF,\mathbf{u}a} = \begin{bmatrix} \mathbf{R}_{KF,\mathbf{u}} & \mathbf{0} \\ \mathbf{0} & 10^{-15} \end{bmatrix}$$

Simulation comparison

Comparing closed-loop performance of the system with the same CSC and different VS controllers

VDE disturbance, initial amplitude -10 cm

Tuning parameters chosen so that reasonable responses are obtained with different local models: LMNE, LM52, LM53, LM59, LM60 and with a disturbance at β_p and l_i (persistent disturbance)

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

Results

ctLQG is more robust to change of local dynamics than SOF; with tuning for model LMVS remains stable with the most challenging model LMNE.
  SOF requires detuning for stable response with LMNE, which deteriorates performance with other models.

In short-term VDE response, ctLQG acts faster than SOF due to faster u_{VS1} response (control from v_p not x_{ic}).
  This also leads to improved response at the CSC level: faster and with less overshoot.

Additional loop from z_p improves response both with SOF and ctLQG, without jeopardising robustness.

The study shows potential for both faster and more robust response to disturbances.
  Best implementation and integration with the CSC layer is yet to be explored.