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Model predictive control of ITER plasma current and shape using SVD

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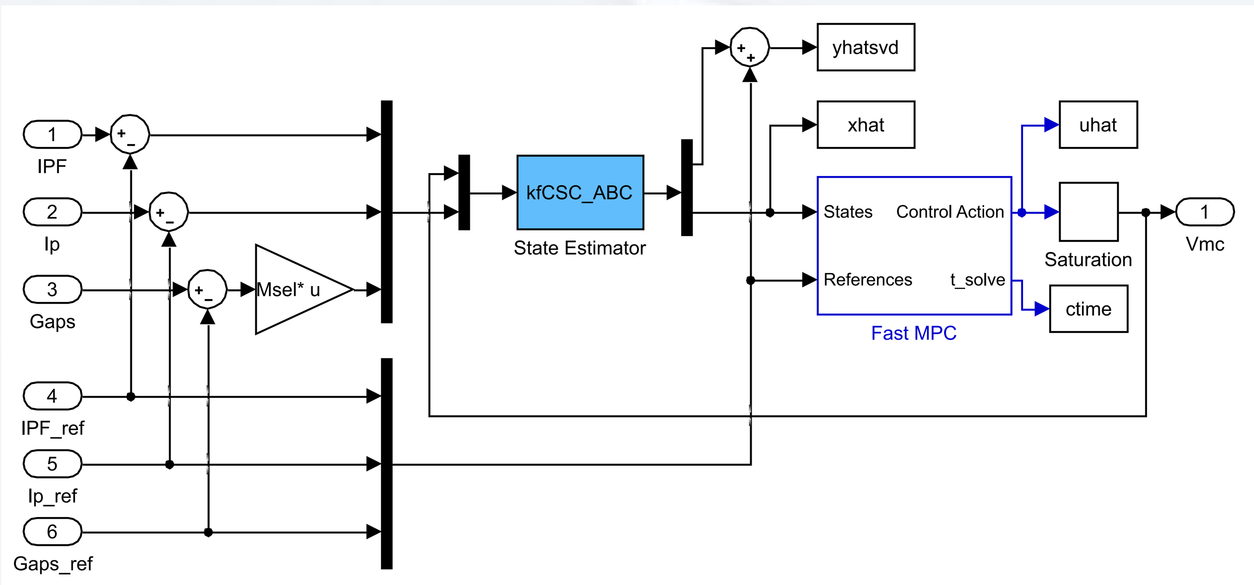
Overview

- Plasma Current and Shape Controller (PCSC) for the flat-top phase of ITER Scenario 1
- Fast Model Predictive Control (MPC) using a dual Fast Gradient Method (dFGM) quadratic programming (QP) solver
- The number of plasma shape geometrical descriptors (output space dimension) reduced using Singular Value Decomposition (SVD)



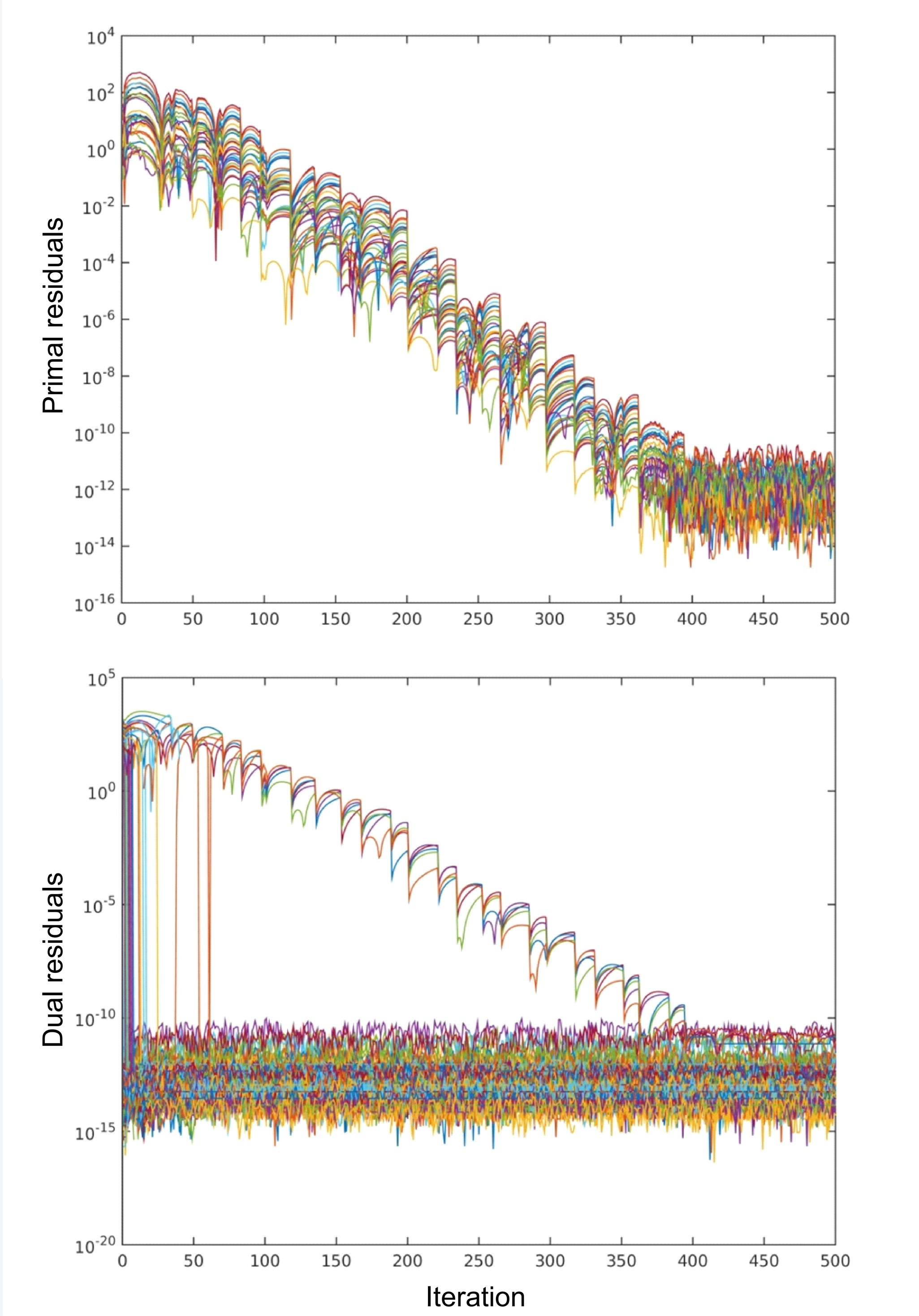
SVD-based fast MPC PCSC block scheme

Output space reduction using SVD

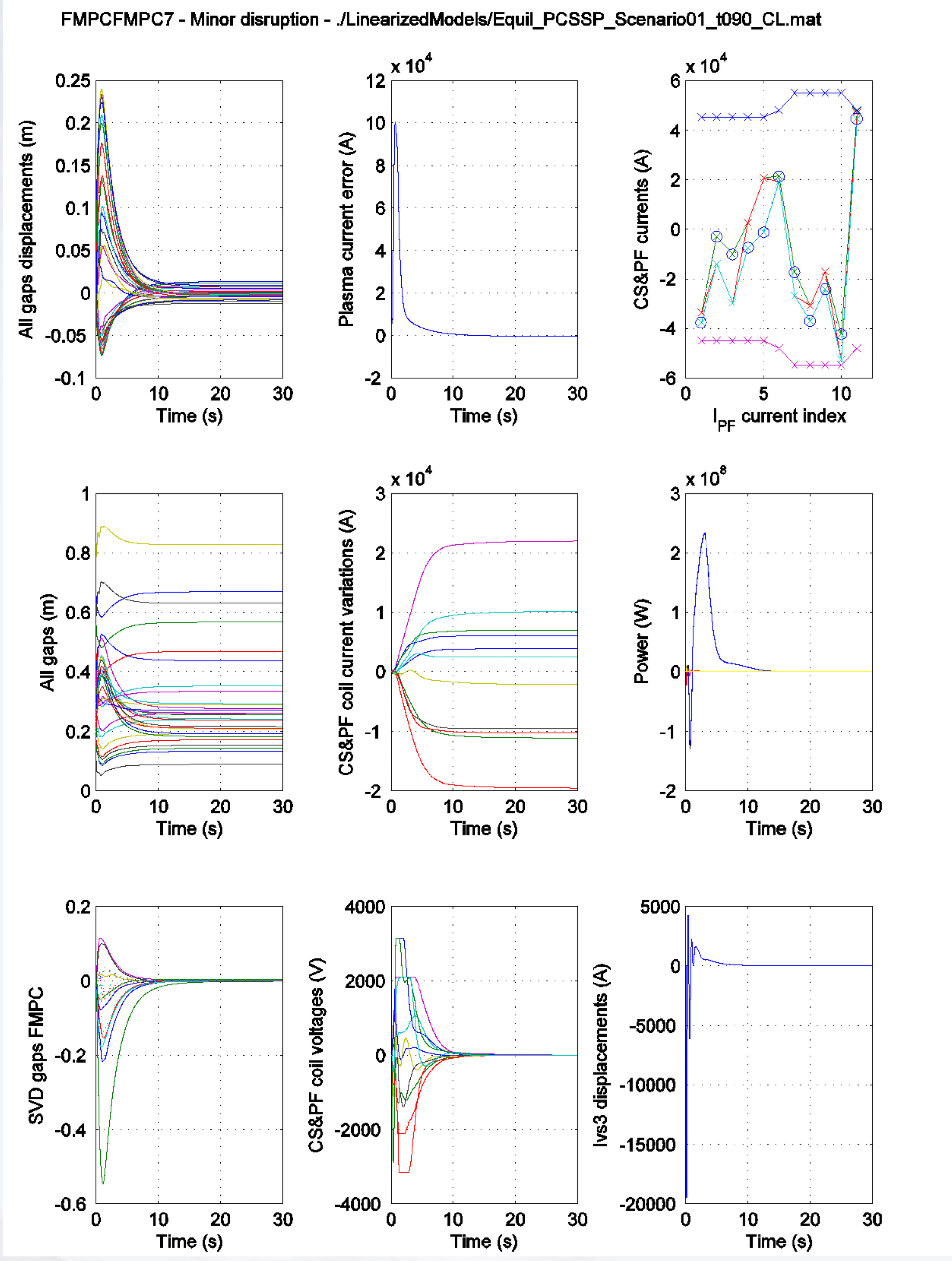
The output dimension is reduced considering the steady-state relation between the poloidal field & central solenoid currents $\mathbf{I}_{PF}$ and the plasma shape geometrical descriptors $\mathbf{g}$ using SVD, where the aim is to achieve a minimum weighted tracking error $(\mathbf{g}-\mathbf{g}_{ref})'\mathbf{Q}_{SVD}(\mathbf{g}-\mathbf{g}_{ref})$ in the steady state, while also striving towards low steady-state control effort $(\mathbf{I}_{PF}-\mathbf{I}_{PF,ref})'\mathbf{R}_{SVD}(\mathbf{I}_{PF}-\mathbf{I}_{PF,ref})$.

Solving QP problems for MPC using dFGM

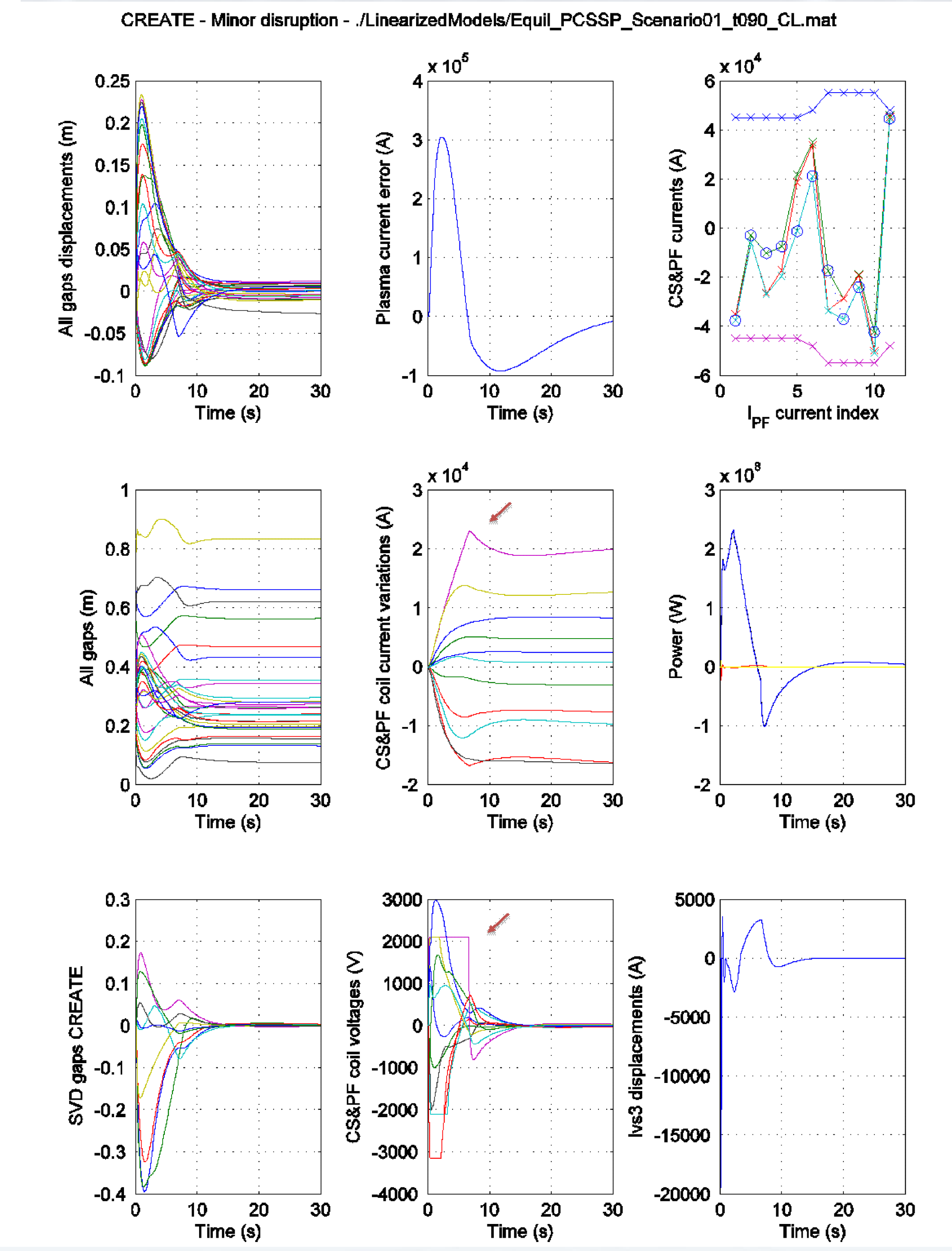
In MPC, a QP optimisation problem must be solved in each time step of the algorithm, which poses a problem with large-scale multivariable systems with fast dynamics. Using complexity reduction techniques for MPC and code optimisation, peak computation times under 7 ms were achieved with the dFGM algorithm, which is able to consider soft state constraints for the enforcement of $\mathbf{I}_{PF}$ constraints.



Example of convergence of primal and dual residuals in dFGM iterations for one time step of MPC



FMPC7-SVD PCSC: Minor Disruption, model t090



CREATE v2d0 PCSC: Minor Disruption, model t090

Simulation closed-loop performance evaluation

The proposed **SVD-based FMPC PCSC** was compared to a reference **CREATE v2d0** controller based on SVD and multivariable PID

with local models corresponding to the operating points of the ITER Scenario 1:
- t = 80 s,
- t = 90 s,
- t = 520 s

with the following disturbances:
- Minor Disruption,
- Uncontrolled ELM,
- L-H Transition,
- H-L Transition,
- Vertical Displacement Event,

using the same Vertical Stabilisation controller.

Simulations with linear plasma model t080

	Minor Disruption		Uncontrolled ELM		LH transition		VDE	
param\sim	Min_V2D0	Min_FMPC	ELM_V2D0	ELM_FMPC	L-H_V2D0	L-H_FMPC	VDE_V2D0	VDE_FMPC
dGapsMax	0,208	0,216	0,021	0,022	0,161	0,154	0,274	0,298
sumdGapsEnd	0,126	0,034	0,026	0,007	0,115	0,058	0,000	0,000
avgRISEdGaps	0,161	0,115	0,017	0,015	0,171	0,140	0,010	0,025
minGap	0,052	0,076	0,097	0,097	0,018	0,034	0,085	0,084
maxDIp	3,0324E+05	1,0838E+05	1,0466E+04	1,0474E+04	1,5694E+05	5,1155E+04	1,2792E+05	1,3707E+05
RISEDIp	5,5130E+05	8,3988E+04	9,7460E+03	5,6404E+03	2,8019E+05	4,5647E+04	2,6536E+04	5,1284E+04
minIPF2bound	3,5066E+03	3,4124E+03	2,0047E+03	1,9842E+03	3,5312E+03	3,5312E+03	3,5179E+03	3,4867E+03
sumIpfERRatEnd	7,7991E+04	6,1802E+04	2,2246E+04	1,7674E+04	1,0610E+05	8,3138E+04	5,5357E+00	2,3051E+01
sumRISEdIPF	4,1527E+05	3,4776E+05	1,1397E+05	9,1449E+04	5,2855E+05	4,1362E+05	7,2442E+02	1,0501E+04
maxAbsdIPF	1,8990E+04	1,4543E+04	4,5086E+03	3,9353E+03	2,2712E+04	2,0682E+04	7,8300E+02	1,2252E+03
maxTotalPower	1,7677E+08	1,9506E+08	1,8450E+07	1,3300E+07	9,8579E+07	1,5407E+08	1,1898E+08	7,7534E+07
RISEtotalPower	3,0750E+08	2,7185E+08	1,3321E+07	2,4959E+07	2,1310E+08	2,6242E+08	1,9106E+07	5,5669E+07
sumRISEvpf	3,4135E+04	3,2896E+04	6,7978E+03	6,6911E+03	2,6850E+04	2,7281E+04	2,4677E+03	1,3773E+04

Simulations with linear plasma model t090

	Minor Disruption		Uncontrolled ELM		H-L transition		VDE	
param\sim	Min_V2D0	Min_FMPC	ELM_V2D0	ELM_FMPC	H-L_V2D0	H-L_FMPC	VDE_V2D0	VDE_FMPC
dGapsMax	0,234	0,240	0,025	0,026	0,149	0,145	0,234	0,251
sumdGapsEnd	0,189	0,150	0,046	0,027	0,084	0,032	0,000	0,000
avgRISEdGaps	0,202	0,147	0,019	0,017	0,170	0,140	0,014	0,027
minGap	0,020	0,052	0,101	0,101	0,018	0,022	0,084	0,083
maxDIp	3,0457E+05	1,0045E+05	2,0393E+04	1,1861E+04	1,9132E+05	6,8587E+04	1,3439E+05	1,4249E+05
RISEDIp	6,1298E+05	8,6592E+04	4,1441E+04	8,7903E+03	3,2723E+05	6,1710E+04	3,7359E+04	5,8860E+04
minIPF2bound	1,8083E+03	4,9436E+02	3,4996E+03	3,4987E+03	1,3266E+03	1,2108E+03	3,4614E+03	2,8611E+03
sumIpfERRatEnd	1,0187E+05	1,0391E+05	2,7732E+04	2,5615E+04	6,3915E+04	4,7972E+04	1,1648E+01	2,9925E+01
sumRISEdIPF	5,2379E+05	5,2107E+05	1,4140E+05	1,3009E+05	3,1277E+05	2,3712E+05	1,1242E+03	9,7327E+03
maxAbsdIPF	2,2986E+04	2,1958E+04	5,5986E+03	5,4206E+03	1,3784E+04	1,2362E+04	1,0971E+03	1,4651E+03
maxTotalPower	2,2983E+08	2,3359E+08	3,4830E+07	1,7784E+07	3,2633E+07	1,0169E+08	1,8050E+08	1,3758E+08
RISEtotalPower	3,9702E+08	3,2306E+08	3,1960E+07	3,2113E+07	5,3384E+07	1,1453E+08	3,9806E+07	8,1480E+07
sumRISEvpf	3,6098E+04	3,3308E+04	8,3180E+03	8,1260E+03	1,5929E+04	1,7464E+04	3,7658E+03	1,3868E+04

Simulations with linear plasma model t520

	Minor Disruption		Uncontrolled ELM		H-L transition		VDE	
param\sim	Min_V2D0	Min_FMPC	ELM_V2D0	ELM_FMPC	H-L_V2D0	H-L_FMPC	VDE_V2D0	VDE_FMPC
dGapsMax	0,428	0,345	0,052	0,050	0,178	0,179	0,235	0,248
sumdGapsEnd	0,399	0,584	0,116	0,095	0,297	0,523	0,000	0,000
avgRISEdGaps	0,369	0,226	0,043	0,038	0,178	0,178	0,015	0,029
minGap	-0,018	0,019	0,093	0,093	0,024	0,017	0,081	0,081
maxDIp	5,4925E+05	1,4940E+05	6,7872E+04	6,0678E+04	1,3194E+05	7,6061E+04	1,6461E+05	1,7094E+05
RISEDIp	9,6561E+05	1,6684E+05	1,2991E+05	3,2687E+04	2,0168E+05	6,7864E+04	5,3508E+04	7,7301E+04
minIPF2bound	-1,7782E+04	2,2760E+02	1,6474E+03	1,9962E+02	-4,5891E+03	2,1307E+02	3,8288E+03	3,7154E+03
sumIpfERRatEnd	1,4131E+05	1,2304E+05	4,1894E+04	6,7423E+04	1,0885E+05	1,6070E+05	2,2187E+01	3,8749E+01
sumRISEdIPF	7,4979E+05	6,0491E+05	2,1735E+05	3,4299E+05	5,3922E+05	6,7386E+05	1,4986E+03	1,1036E+04
maxAbsdIPF	3,7101E+04	2,8805E+04	9,0743E+03	1,5746E+04	2,3895E+04	3,9448E+04	1,1879E+03	1,7675E+03
maxTotalPower	4,3702E+08	2,6375E+08	1,2858E+08	7,4321E+07	1,0961E+08	1,6689E+08	2,0125E+08	2,2018E+08
RISEtotalPower	1,0242E+09	4,1512E+08	1,3256E+08	1,1723E+08	1,3694E+08	4,1603E+08	4,8022E+07	1,1992E+08
sumRISEvpf	5,8517E+04	4,2359E+04	1,4759E+04	1,9590E+04	2,6911E+04	5,3224E+04	4,5039E+03	1,2920E+04

Performance Measures:

- maximal gap displacement from the reference,
- sum of gap displacements at the end of simulation,
- average of RISE* value for all gap displacements,
- smallest gap of plasma shape to the chamber wall,
- maximal plasma current displacement δI_p,
- RISE value of δI_p,
- displacement of the closest $\mathbf{I}_{PF}$ from its bound,
- sum of $\mathbf{I}_{PF}$ displacements from the equilibrium value,
- sum of RISE of all $\mathbf{I}_{PF}$ displacements from equilibrium,
- maximal $\mathbf{I}_{PF}$ displacement from equilibrium,
- peak value of total power consumption,
- RISE value of total power consumption,
- sum of RISE of all $\mathbf{V}_{PF}$ voltages.

* Root of Integral Square Error

Conclusions

The SVD-based MPC PCSC is computationally feasible for ITER, with peak computation time under 7 ms using a dFGM QP solver.

The performance evaluation in simulation of specific disturbances in different operating points of ITER Scenario 1 generally shows better performance in terms of transient peak, settling time and the steady-state offset of gaps, and a much better performance in tracking of the plasma current than the reference scheme with most disturbances.

It can avoid superconductive current saturations, which is not the case with the reference scheme, and in some cases shows better performance regarding voltage saturations.

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COSYLAB

Slovenian Research Agency

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