

GRID EMT

SIMULATION INITIATIVE

Control Design for EMT

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Motivation

- EMT simulation platforms lack control design features
- Control design based on linearized models: not integrated with EMT platforms
- Linearized models do not have tunable bandwidth
- Linearization performed using numerical perturbation: scalability challenge
- Objective: Develop a scalable linearization and control design tool with tunable bandwidth as an add-on feature to the RE-INTEGRATE platform



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Approach: Fundamentals of DP

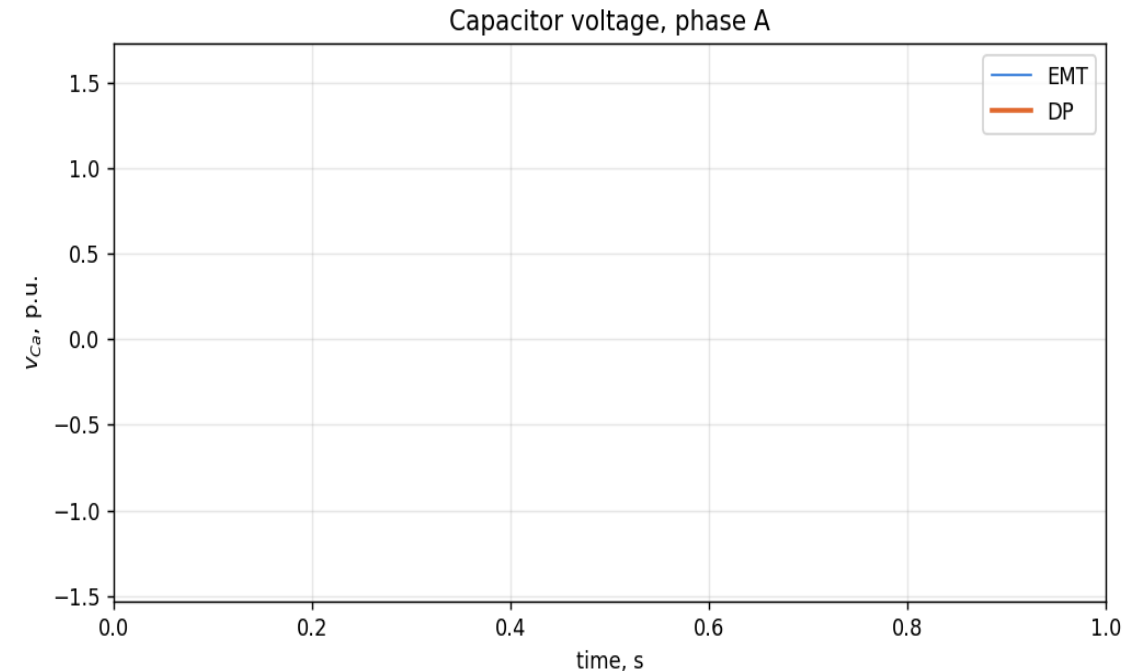
Dynamic Phasor (DP): A near-periodic time-domain waveform $x(\tau)$ can be expressed as,

$$x(\tau) = \sum_{k=-\infty}^{\infty} X_k(t) e^{jk\omega_s \tau} \text{ for } \tau \in (t - T, t], \quad k \in \mathbb{Z}$$
$$\omega_s = \frac{2\pi}{T}, \quad \mathbf{X}_k(t) \equiv \langle x \rangle_k \text{ are complex Fourier}$$

coefficients called DPs.

Why DP?

- Time-invariant
- Tunable bandwidth of model
- Captures inter-frequency band coupling
- Ideally suited for periodically switched components (e.g., power electronics)
- Ideally suited for control design in EMT models



Approach: linearization and control design framework

- Non-linear state space system (in DP):

$$\langle \dot{x} \rangle = f(\langle x \rangle, \langle u \rangle)$$

- At steady state operating point (x_o, u_o) :

$$f(\langle x_o \rangle, \langle u_o \rangle) = 0$$

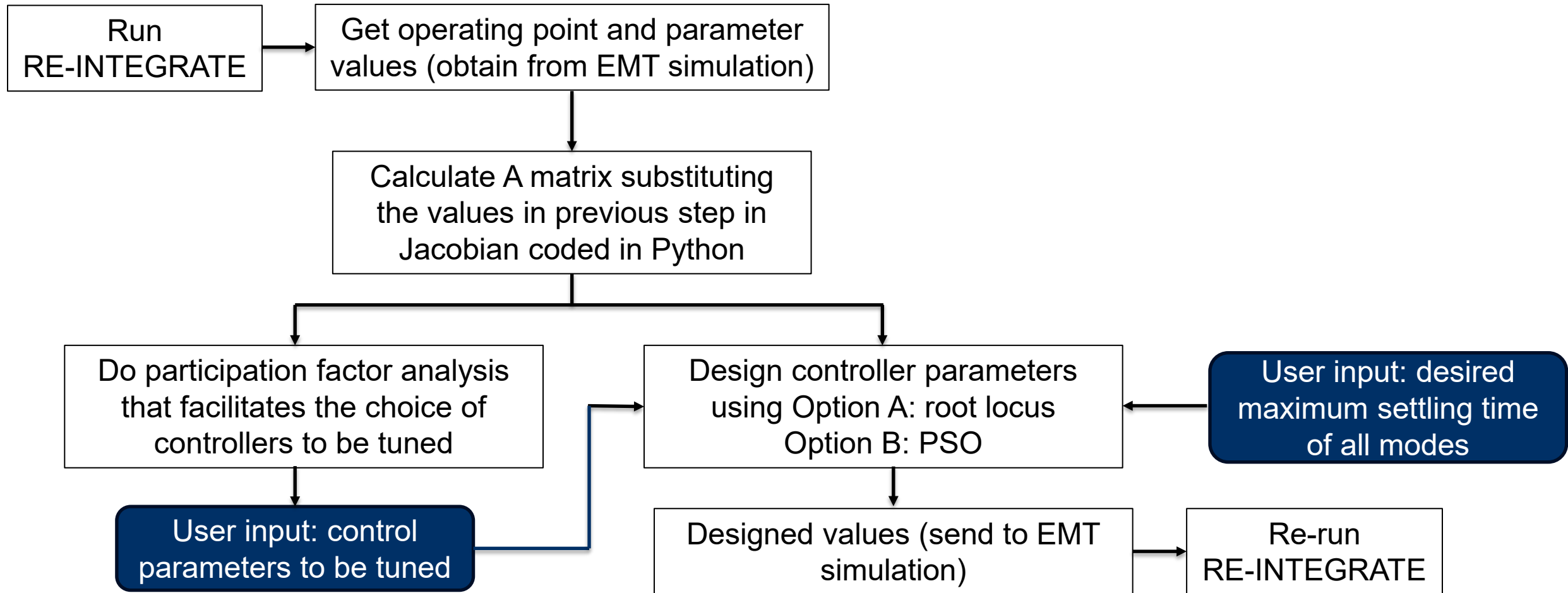
- Linearized system (in DP):

$$\langle \dot{x} \rangle = A(p)\langle x \rangle + B(p)\langle u \rangle \quad \text{where, } A(p) = \left. \frac{\partial f}{\partial \langle x \rangle} \right|_{(\langle x_o \rangle, \langle u_o \rangle)} \quad \text{and} \quad B(p) = \left. \frac{\partial f}{\partial \langle u \rangle} \right|_{(\langle x_o \rangle, \langle u_o \rangle)}$$

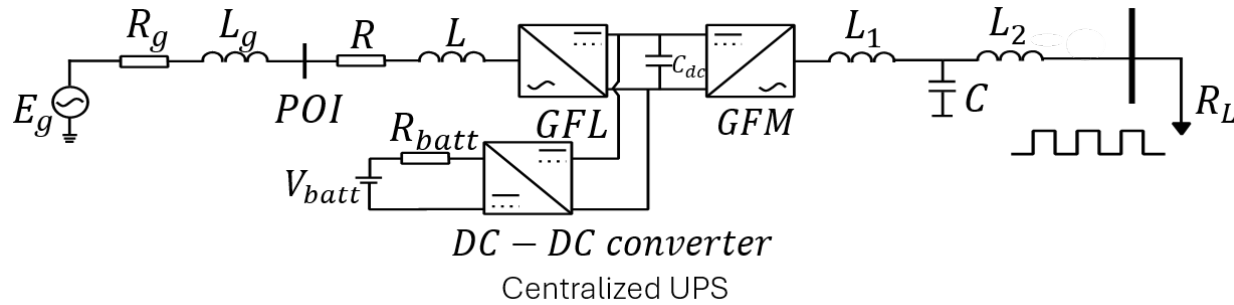
- p is the set of control design parameters.
- The Jacobians are calculated analytically to reduce computational burden.
- Eigenvalues of A change continuously with p .



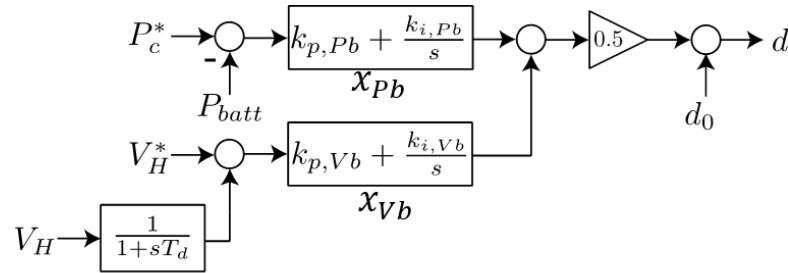
Workflow



Use case: AI DC UPS controller design

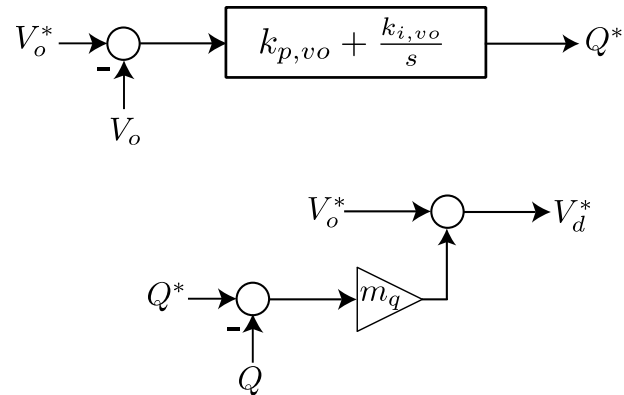


DC-DC converter control



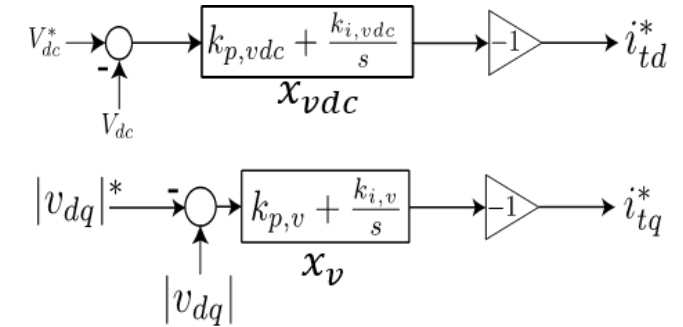
Voltage and power regulator

GFM control

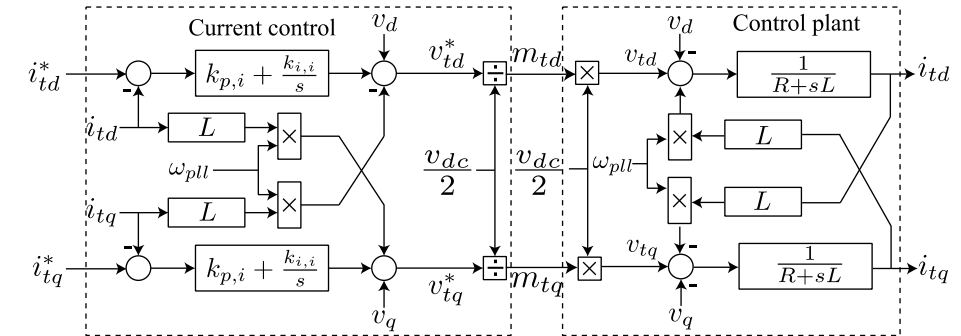


Output voltage magnitude control

GFL control



DC link voltage and AC voltage magnitude control

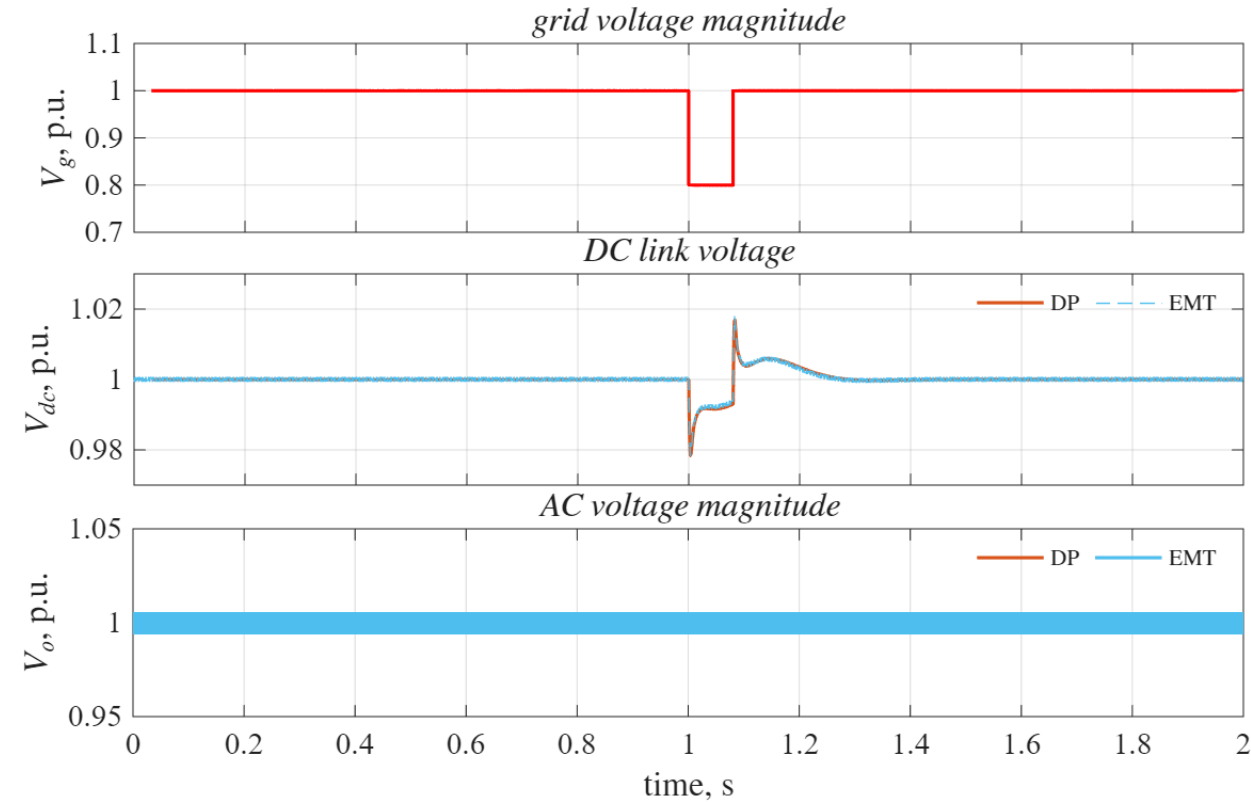


Current control and filter

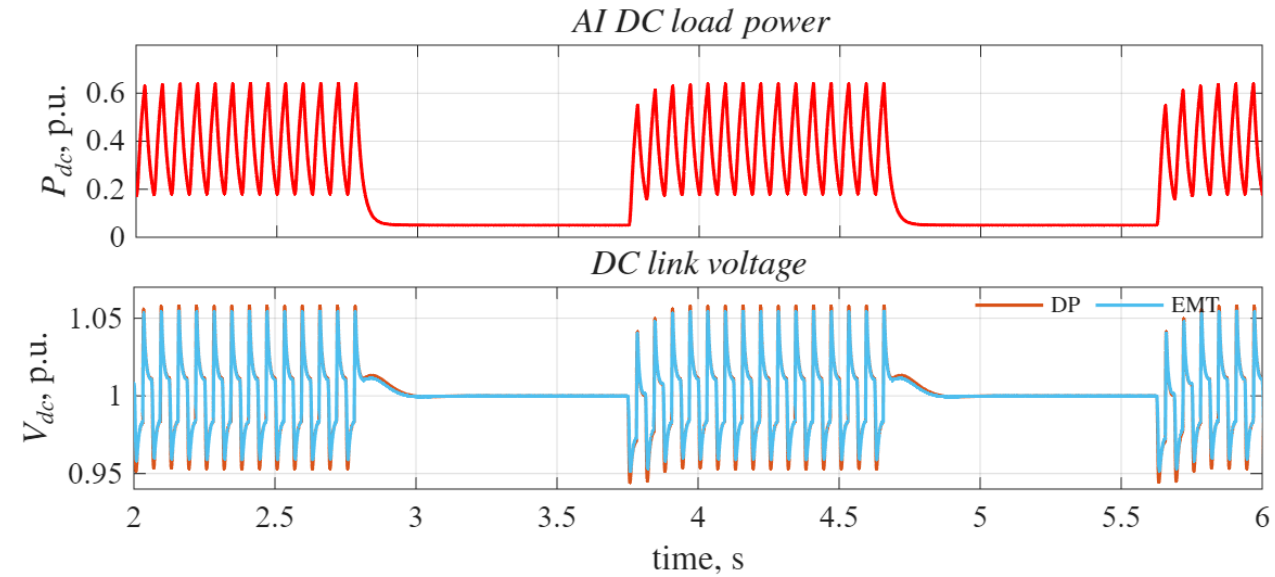


EMT-vs-DP benchmarking: AI DC UPS example

- Test case: Grid voltage dip



- Test case: AI DC load fluctuation



Eigen decomposition and participation factor analysis

- Participation factor analysis reveals the presence of poorly damped complex-conjugate eigenvalue pairs, primarily caused by improperly tuned controllers.

$\lambda_1 = 0.000000 + 0.000000j$
 $\lambda_2 = -0.000000 + 0.000000j$
 $\lambda_3 = -13.433604 + 0.000000j$
 $\lambda_4 = -16.900322 - 16.495905j$
 $\lambda_5 = -16.900322 + 16.495905j$
 $\lambda_6 = -110.240791 + 0.000000j$
 $\lambda_7 = -174.235593 + 0.000000j$
 $\lambda_8 = -247.537505 + 0.000000j$
 $\lambda_9 = -351.100312 - 658.462811j$
 $\lambda_{10} = -351.100312 + 658.462811j$
 $\lambda_{11} = -755.496264 + 0.000000j$
 $\lambda_{12} = -771.561537 + 0.000000j$
 $\lambda_{13} = -871.566858 + 0.000000j$
 $\lambda_{14} = -1000.000000 + 0.000000j$
 $\lambda_{15} = -8077.126871 - 3741.853430j$
 $\lambda_{16} = -8077.126871 + 3741.853430j$
 $\lambda_{17} = -11726.889197 - 12032.951801j$
 $\lambda_{18} = -11726.889197 + 12032.951801j$
 $\lambda_{19} = -41284.195951 + 0.000000j$
 $\lambda_{20} = -48744.499553 + 0.000000j$
 $\lambda_{21} = -376235.622167 + 0.000000j$

Simulink non-linear model		Python	
State	Participation factor	State	Participation factor
$\langle x_{Pd} \rangle_0$	0.2946	$\langle x_{Pd} \rangle_0$	0.2946
$\langle x_{Pb} \rangle_0$	0.2568	$\langle x_{Pb} \rangle_0$	0.2568
$\langle x_{vdc} \rangle_0$	0.2434	$\langle x_{vdc} \rangle_0$	0.2434
$\langle x_{Vb} \rangle_0$	0.1892	$\langle x_{Vb} \rangle_0$	0.1892

x_{Pb} : DC-DC converter power regulator state

x_{Vb} : DC-DC converter voltage regulator state

x_{vdc} : GFL DC link voltage controller state



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Design approach: root locus

- Scale the controller parameters by a gain factor.
- Track the movement of the closed-loop eigenvalue pairs as the gain factor varies.
- Identify the gain factor that satisfies the settling-time requirement.
- Select the corresponding controller parameters as the final design.

FINAL OUTPUT

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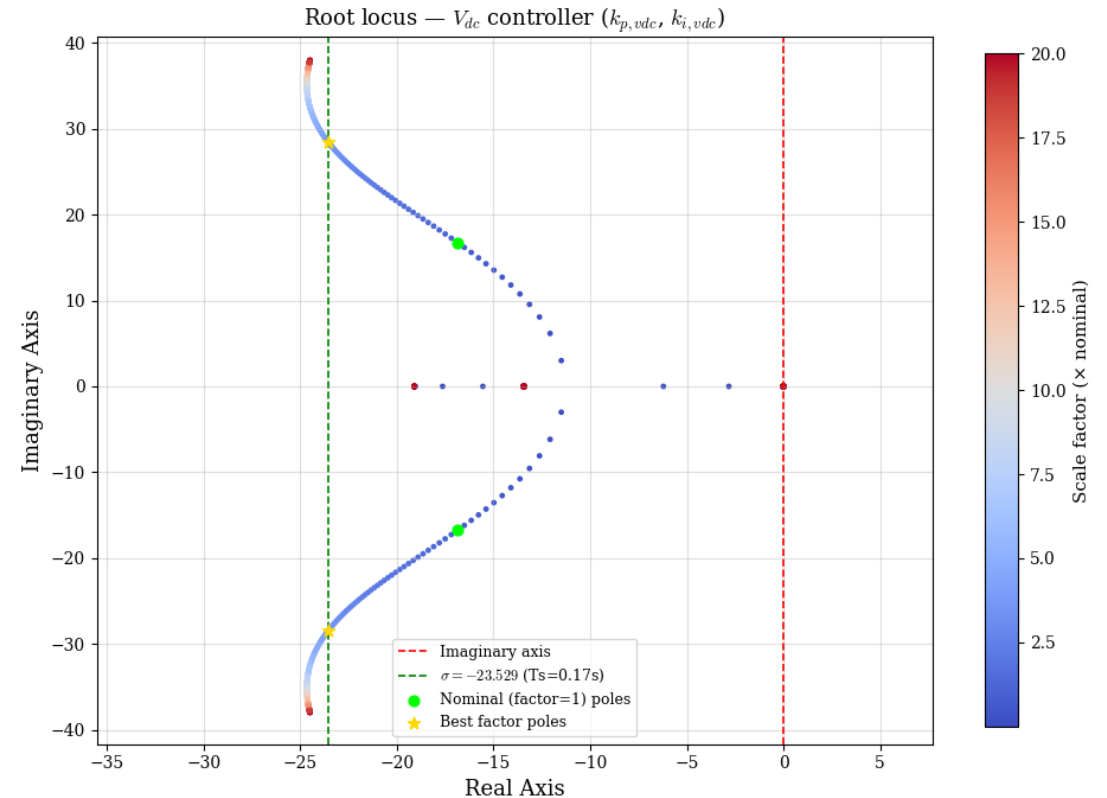
$k_{p_vdc} = 35.4181$

$k_{i_vdc} = 3.7579$

(scale factor = $3.5418 \times \text{nominal}$)

Estimated settling time < 0.17 s

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Design approach: particle swarm optimization (PSO)

- Unlike previous approach, PSO allows to design controller parameters simultaneously within a search space solving an optimization problem.
- In addition, the controllers can be designed considering multiple operating conditions.
- Objective function:

$$\begin{aligned} & \min_{K_i, i=1,2,\dots,6} (F + L) \\ \text{s.t. } & K_{i,\min} \leq K_i \leq K_{i,\max} \quad \forall i = 1, 2, 3, \dots, 6 \\ & F = \frac{1}{6} \sum_{i=1}^6 \frac{K_i}{K_{\text{nom}}} \\ & L = \begin{cases} 0 & \text{if } \text{Re}(\lambda_p^{(j)}) < -\sigma_{\min} \quad \forall p \quad \forall j = 1, \dots, 5 \\ 10^6 & \text{otherwise} \end{cases} \end{aligned}$$

FINAL OUTPUT

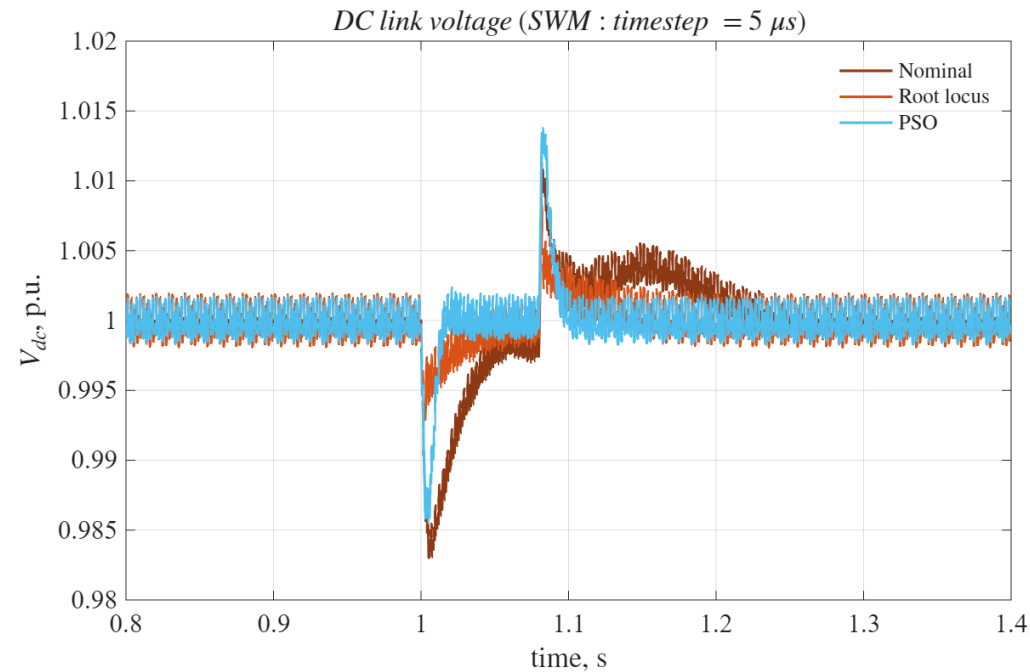
Designed for 5 operating conditions

- sk_p_vdc = 10, sk_i_vdc = 4.55141
- sk_p_Pb = 1.66232, sk_i_Pb = 0.18484
- sk_p_Vb = 1, sk_i_Vb = 0.530985
- sk_p_vo = 10, sk_i_vo = 26.5258



Comparison between design approaches

- Controllers designed via PSO achieved less settling time compared to root locus.
- PSO allows to search controller parameters in a broader region while solving an optimization problem under specified constraints.
- Since overshoot is not specified in the set of constraints, performance of controllers designed by PSO show higher overshoot.



Comparison of performances of the controllers designed using root locus and PSO against nominal controller (Switched model of the converters assumed)



Conclusions/Next Steps

- Complete the interface with RE-INTEGRATE platform
- Refine the control design
- Extend the tool for more complex data center architecture
- Introduce option of higher-order DPs in control design if needed



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Thank You

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