Hitachi Energy

Linearization of Power Electronics in Power System

Xing Huang, Hitachi Energy

MATLAB EXPO

Linearization of Power Electronics in Power System

MATLAB EXPO China 2022

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Content

01_About Hitachi Energy (Go Live in China since March 30, 2022)

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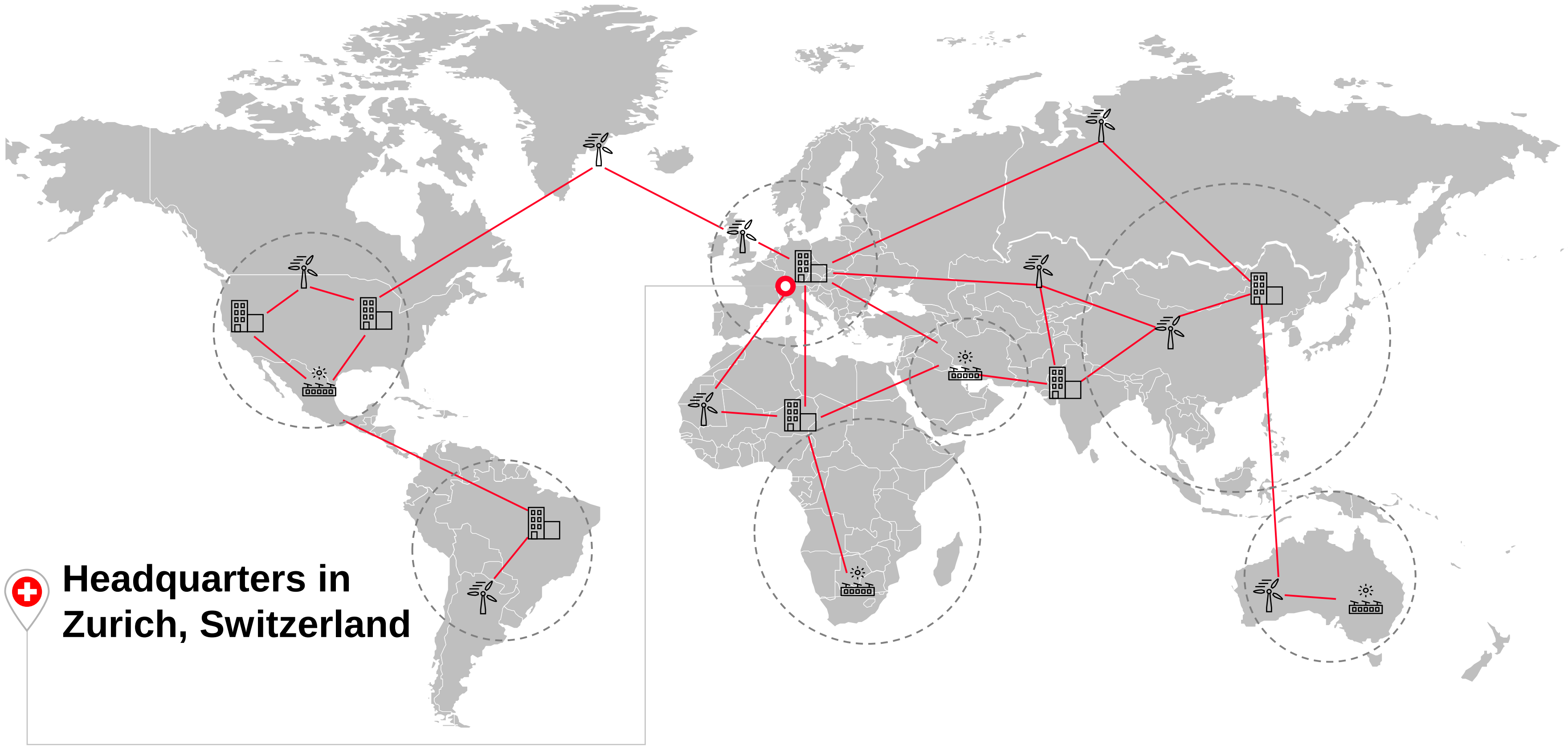


38,000 employees

90+ countries with 200 offices

~250 years' heritage combined

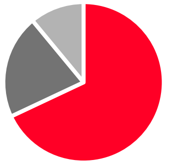
5,500 sales employees & field engineers

2,000 engineers & scientists in R&D

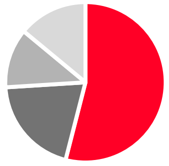
Four Business Units

Grid Automation	High Voltage Products
Grid Integration	Transformers

Customers



Offering



Geographies

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One Global R&D Organization

Our R&D team is present in 20+ countries and we have Research Centers in seven countries

2000+
R&D experts

>60%
work in software development

~200 researchers

>80%
researchers have Ph.D.

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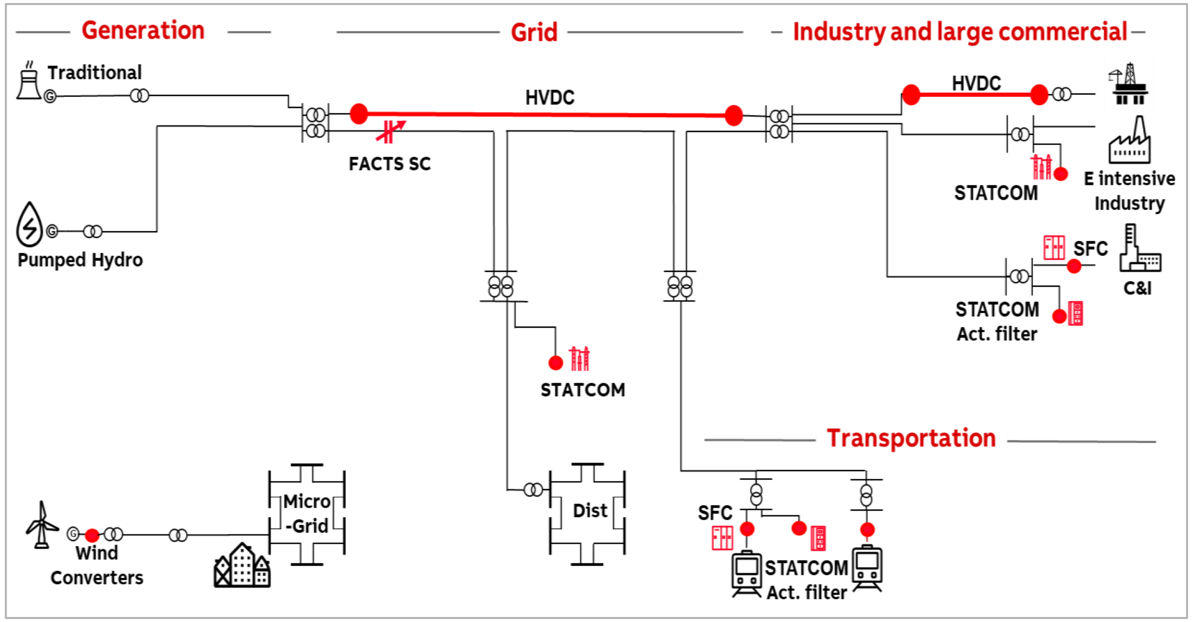
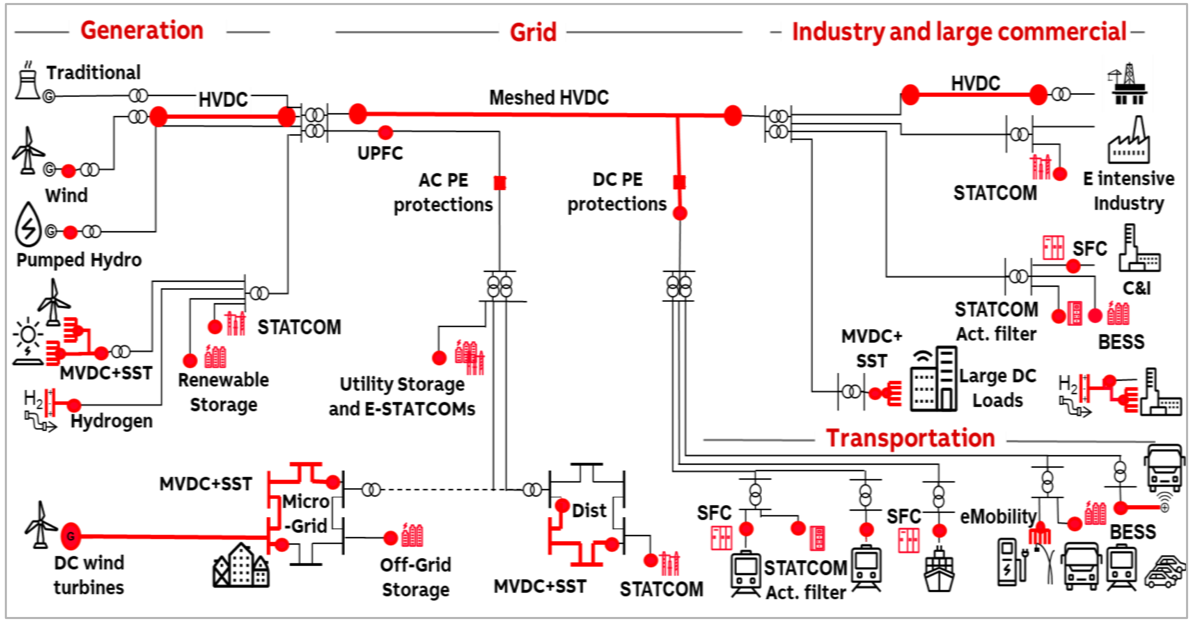
Past … The conventional utility grid



Power Electronics a niche application

Future … The carbon-neutral future is electric



Power Electronics across the total Power Grid

Technology Trends: Power Electronics coupled with Digital enables electricity to be the backbone of the carbon-neutral future

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02_Stability Issues for Future Power Systems

Stability Problems

- Power Oscillation [1]
  - between converters
  - between converters and utility
- Sub-synchronous Oscillation
  - Between PV/Wind converters and utility [2]
- Power System Accident
  - Xinjiang, China, 2015 [3]
  - Texas, USA, 2019 [4]
  - Hubei, China, 2011 [5]

Stability Analysis Methods

- Modal Analysis (模态分析法，特征值分析法)
  - Eigenvalue locus (根轨迹)
  - Participation factor method (参与因子法)
  - Sensitivity analysis (灵敏度)
- Impedance Analysis (阻抗分析)
  - Passivity analysis (无源性分析)
  - Nyquist stability criterion (奈奎斯特稳定判据)
- Phase Amplitude Analysis (幅相动力学)
- …..

Small signal model is required for stability analysis in different methods

[1] Synchronous Reference Frame based Impedance Model and Stability Criterion for Grid-connected Renewable Energy Generation Systems, LIU Huakun, etc., Proceedings of the CSEE, 2017
[2] Sub-synchronous resonance mitigation for series compensated DFIG-based wind farm by using two degree of freedom control strategy[J]. Huang P H, ect., IEEE Transactions on Power Systems，2015，30(3)：1442-1454.
[3] Mechanism and characteristics of subsynchronous oscillation caused by the interaction between full converter wind turbines and AC systems [J]. XIE Xiaorong, LIU Huakun, HE Jingbo, etc. Proceedings of the CSEE, 2016, 36(9): 2366G2372.
[4] A refined frequency scan approach to sub-synchronous control interaction (SSCI) study of wind farms [J]. IEEETransonPowerSystems, 2016, 31(5): 3904G3912.
[5] Investigation of SSR in practical DFIG-based wind farms connected to a series compensated power system [J]. IEEE TransonPowerSystems, 2015, 30(5): 2772G2779.

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Design and Analysis in MATLAB Platform

Simulink Model → Linearize Tools → Accuracy Verification → Stability Analysis & Optimization

- **Time Domain Simulation**: Simulink Model
- **Prepare for Frequency Domain Analysis**: Linearize Tools, Accuracy Verification
- **Frequency Domain Analysis**: Stability Analysis & Optimization

MATLAB is a general simulation platform for multiple purpose

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03_Small Signal Modeling for Complex PE System

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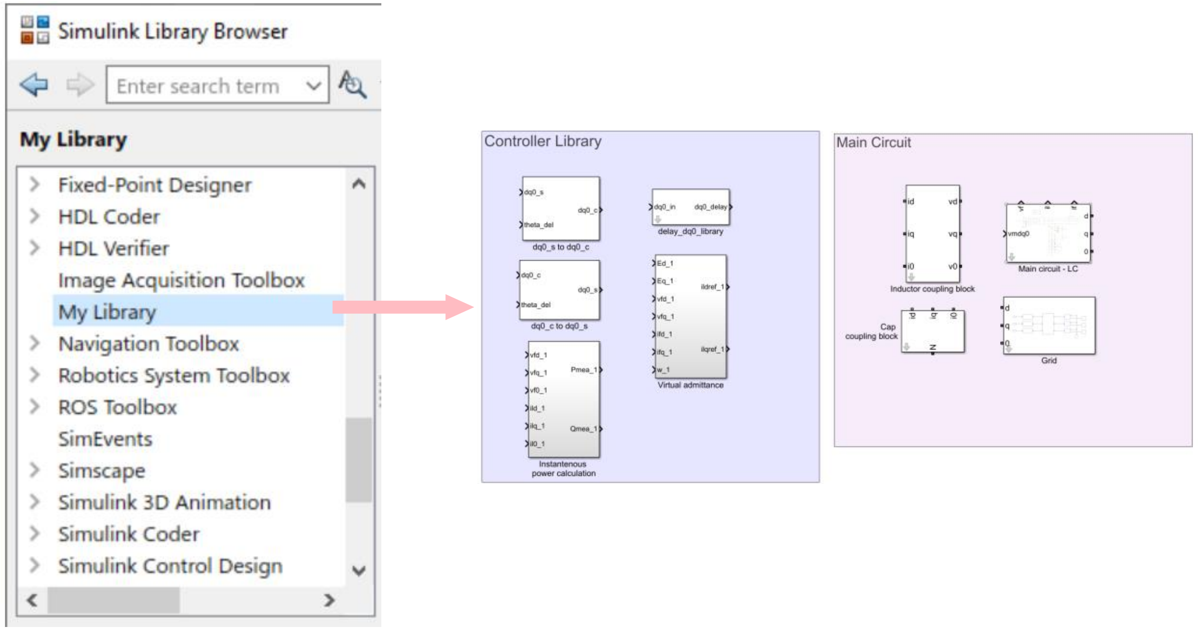
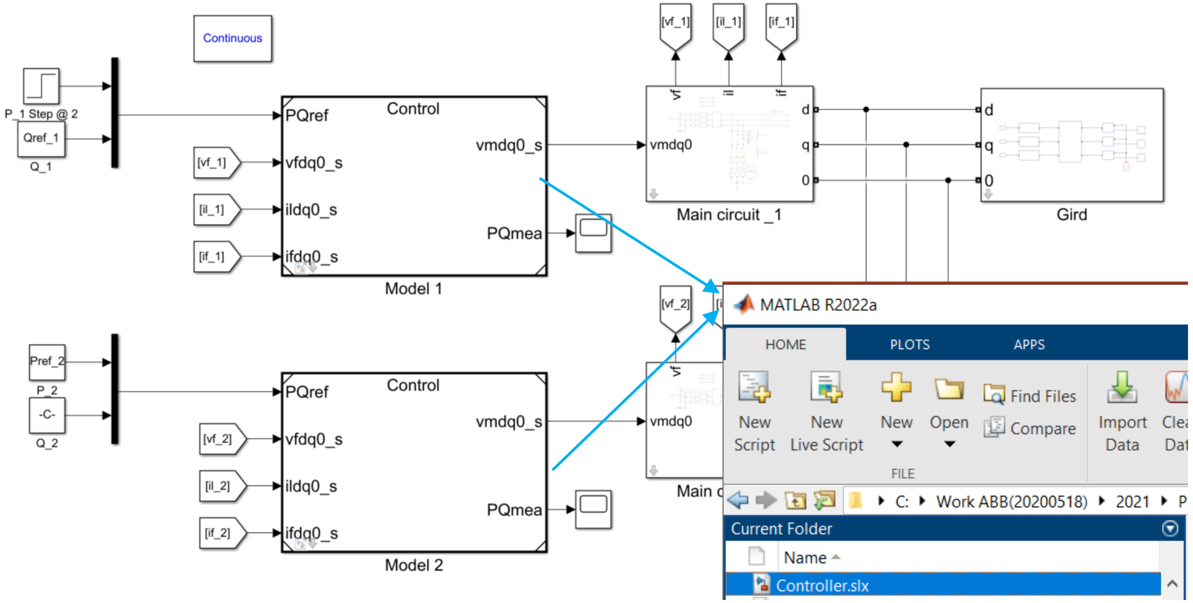
Internal Library Blocks

- Accumulate & Inherit
- Add customized library into Library Browser
- Very Convenient for sharing and reuse

Model Reference

- Very Convenient for Parallel Design and Unit Test
- Code generation can accelerate model simulation
- Incremental loading speeds up model load times





Two ways used for efficient modeling: Internal Library and Model Reference

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03_Small Signal Modeling for Complex PE System

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Comparison Among Multiple Linearization Methods

	Transfer Function	Model Linearizer APP	Frequency Response Estimation
Modeling Time	Long	Short	Short
Simulation Speed	Fast	Fast	Slow
Time Domain Analysis	Yes	Yes	Yes
Frequency Domain Analysis	Yes	Yes	Yes
Recommended Application Area	Simple model	In most cases and for complex model	Simulink model contains discontinuities or non-periodic event-based dynamics

Recommend to use Linearization Tool in professional software for complex PE system

[1] According to sampling theorem, where fs is the sampling frequency.

03_Small Signal Modeling for Complex PE System

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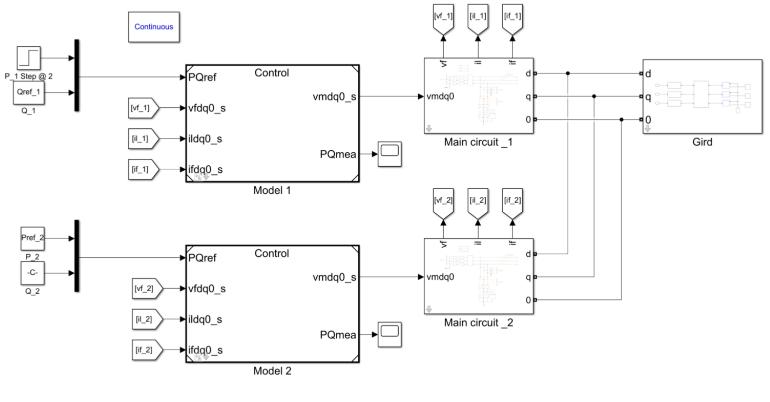
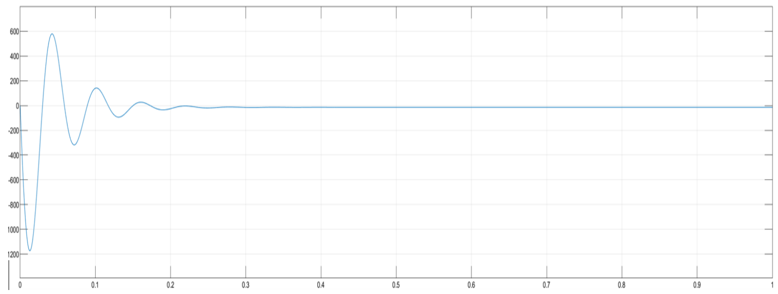
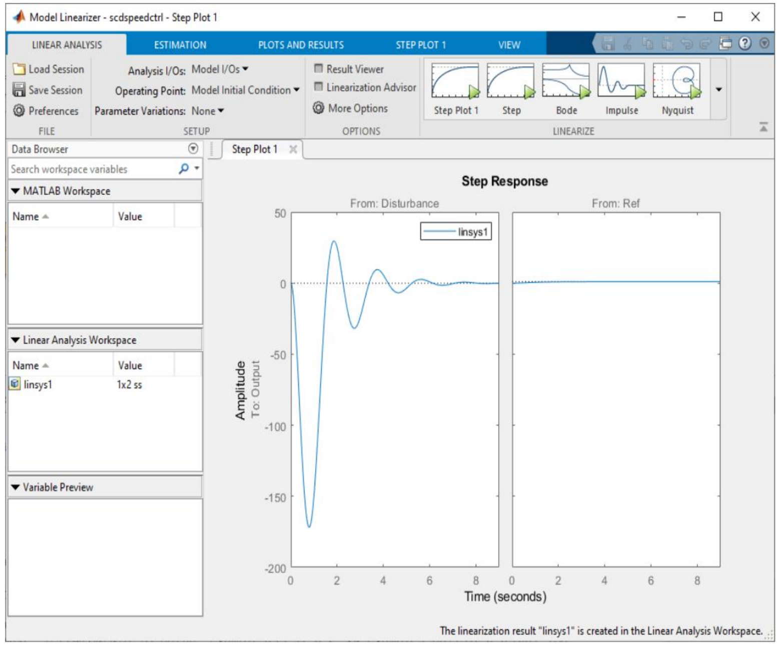
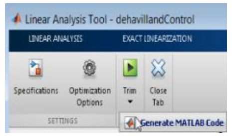
Simulink Model





Model Linearizer APP






```
function op = myoperatingpointsnapshot
%
% MATLAB(R) file generated by MATLAB(R) 7.13 and Simulink Control Design (TM) 3.4.
%% Specify the model name
model = 'dehavillandControl';

%% Run simulation to extract snapshots.
op = findop(model,[5]);
```

Code for Small Signal Analysis

linearize

Linear approximation of Simulink model or subsystem

Syntax

```
linsys = linearize(mdl,io)
linsys = linearize(mdl,io,op)
linsys = linearize(mdl,io,param)
linsys = linearize(mdl,io,blocksub)
linsys = linearize(mdl,io,options)
linsys = linearize(mdl,io,op,param,blocksub,options)

linsys = linearize(mdl,blockpath)
linsys = linearize(mdl,blockpath,op)
linsys = linearize(mdl,blockpath,param)
linsys = linearize(mdl,blockpath,blocksub)
linsys = linearize(mdl,blockpath,options)
linsys = linearize(mdl,blockpath,op,param,blocksub,options)

linsys = linearize( __ ,'StateOrder',stateorder)

[linsys,linop] = linearize( __ )

[linsys,linop,info] = linearize( __ )
```

Re-use the MALTAB/Simulink model to save the model development time

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03_Small Signal Modeling for Complex PE System

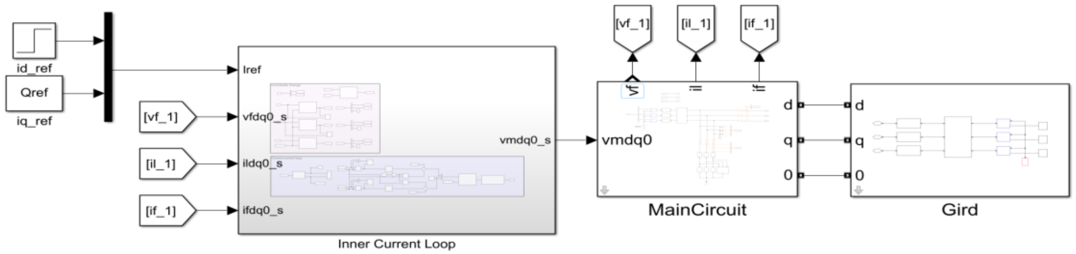
Accuracy Verified in Multiple Models

- Single Converter
  - PLL
  - PR, PI
  - Current Loop (PI)
  - Current Loop (PI) + Time Delay

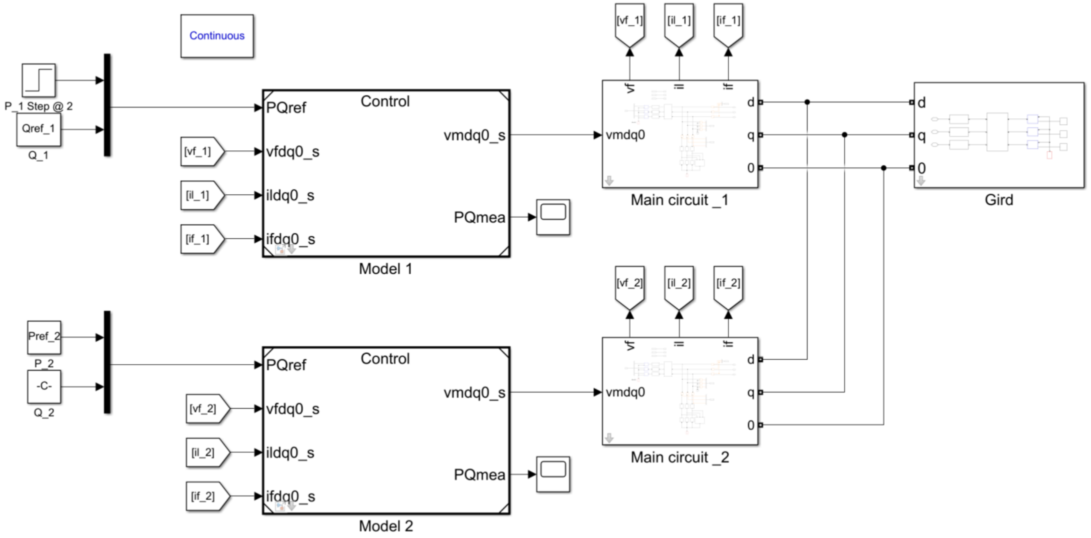
- Converters Parallel
  - Two Converters
  - Ten Converters

Accuracy Verification Examples

- Case1: Single grid connected converter with current control loop



- Case2: Two grid connected converters parallel at AC side



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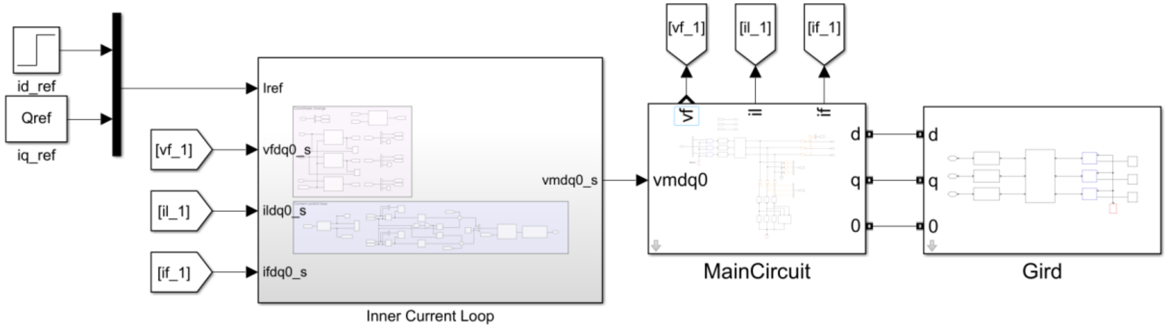
Case 1: Single Converter with Current Control Loop

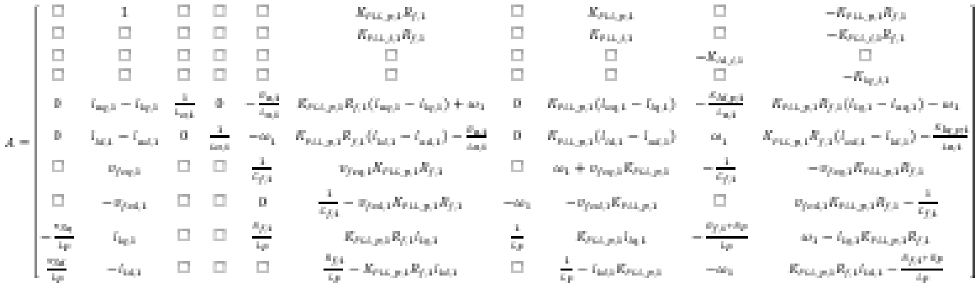


	1	2	3	4	5	6	7	8	9	10		1
1	0	0	314.1593	0	0	0.0844	0	94.2478	0	-0.0844	1	theta_1
2	0	0	0	0	0	0	0	0	-0.3000	0	2	XId_1
3	0	0	0	0	0	0.7608	0	850	0	-0.7608	3	Xw_1
4	0	0	0	0	0	0	0	0	0	-0.3000	4	XIq_1
5	-1.0384e-07	3.9477e+04	8.2243	-3.9329e-07	-35.8974	314.1615	2.2475e-08	2.4673	-11.8431	-314.1615	5	iad_1
6	7.8452e-09	-5.0950e-10	-4.4968e-04	3.9477e+04	-314.1593	-35.8974	-5.0950e-10	-1.3490e-04	314.1593	-11.8431	6	iaq_1
7	0	0	-0.0069	0	1.2028e+04	-1.8631e-06	0	314.1572	-1.2028e+04	1.8631e-06	7	vfcd_1
8	0	0	-314.8546	0	0	1.2028e+04	-314.1593	-94.4564	0	-1.2028e+04	8	vfcq_1
9	313.4641	0	-20.8846	0	4.2205	-0.0056	4.7155e+03	-6.2654	-4.2205	314.1649	9	ild_1
10	4.7050e+03	0	-313.4641	0	0	4.1364	0	4.6214e+03	-314.1593	-4.1364	10	ilq_1

sys_A

10x10 double

	1	2	3	4	5	6	7	8	9	10	
1	0	314.1593	0	0	0	0.0844	0	94.2478	0	-0.0844	$\Delta\theta_1$
2	0	0	0	0	0	0.7608	0	850	0	-0.7608	$\Delta X_{\omega,1}$
3	0	0	0	0	0	0	0	0	-0.3000	0	$\Delta X_{Id,1}$
4	0	0	0	0	0	0	0	0	0	-0.3000	$\Delta X_{Iq,1}$
5	0	8.2243	3.9477e+04	0	-35.8974	314.1615	0	2.4673	-11.8431	-314.1615	$\Delta i_{ad,1}$
6	0	-4.4968e-04	0	3.9477e+04	-314.1593	-35.8974	0	-1.3490e-04	314.1593	-11.8431	$\Delta i_{aq,1}$
7	0	-0.0069	0	0	1.2028e+04	-1.8631e-06	0	314.1572	-1.2028e+04	1.8631e-06	$\Delta v_{fcd,1}$
8	0	-314.8546	0	0	0	1.2028e+04	-314.1593	-94.4564	0	-1.2028e+04	$\Delta v_{fcq,1}$
9	313.4641	-20.8846	0	0	4.2205	-0.0056	4.7155e+03	-6.2654	-4.2205	314.1649	$\Delta i_{ld,1}$
10	4.7050e+03	-313.4641	0	0	0	4.1364	0	4.6214e+03	-314.1593	-4.1364	$\Delta i_{lq,1}$



The state-space matrices exported by MATLAB is verified by using theoretical derivation

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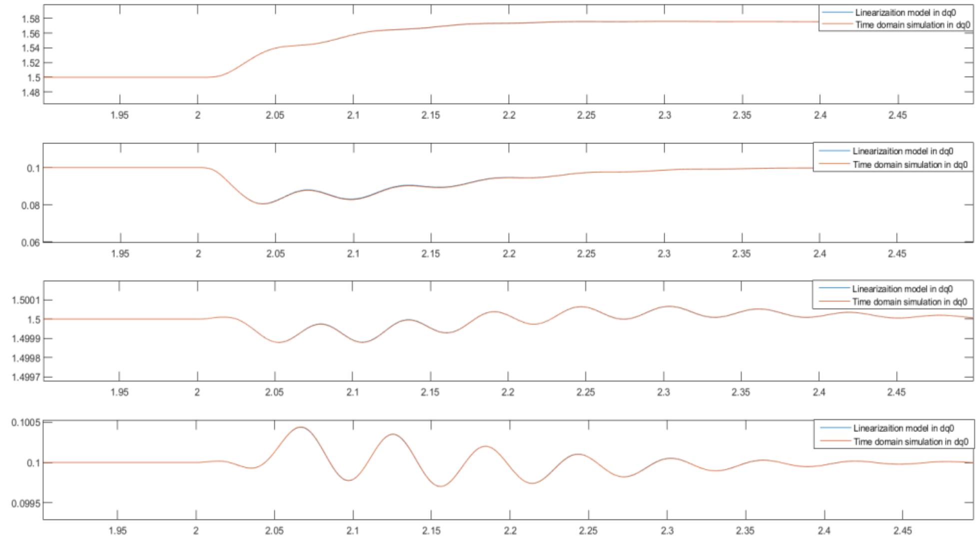
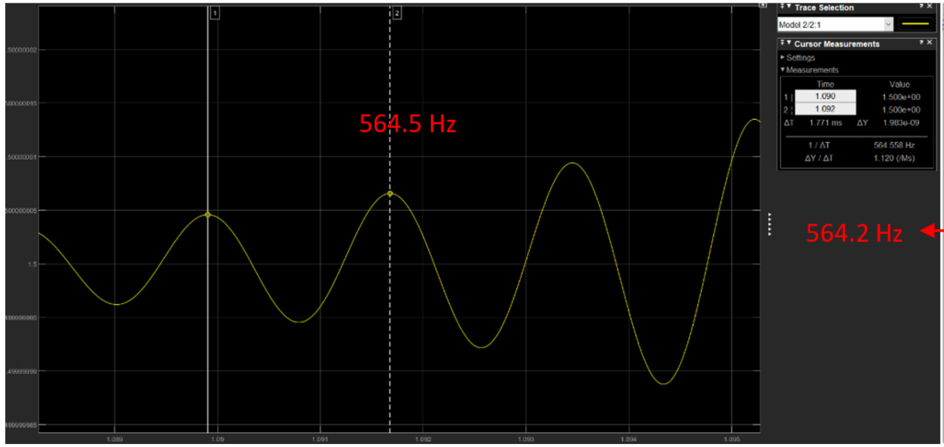
Case2: Two Grid Connected Converters Parallel at AC side

- Stable step-response
  - Two converter parallel
  - A step of 5% applied to active power reference of the 1st converter
  - Alignment between time-domain simulation and linearization model



- Non-stable step-response
  - Two converter parallel
  - A step of 50x gain in PLL is applied to both converters
  - Same unstable frequency in both time-domain simulation and linearization model

From simulation results



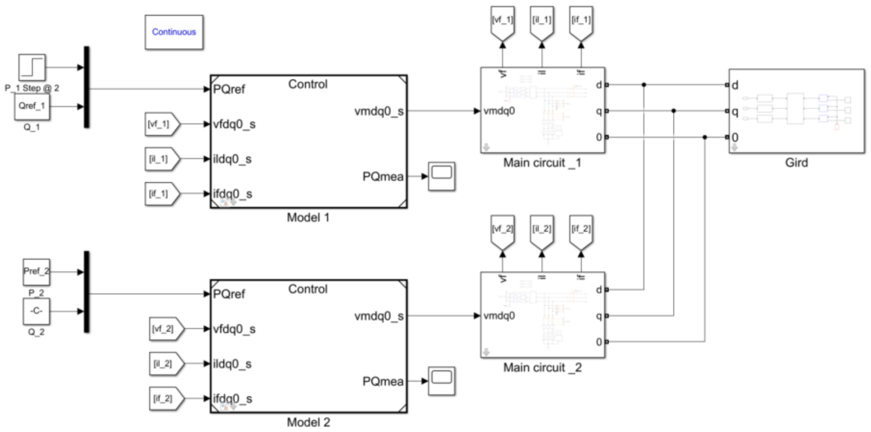
From Linearization

28	-1.1147e+05 + 0.0000e+00i
29	-8.8267e+04 + 8.4209e+04i
30	-8.8267e+04 - 8.4209e+04i
31	-1.1147e+05 + 0.0000e+00i
32	-8.8267e+04 + 8.4209e+04i
33	-8.8267e+04 - 8.4209e+04i
34	-1.1147e+05 + 0.0000e+00i
35	-8.8267e+04 + 8.4209e+04i
36	-8.8267e+04 - 8.4209e+04i
37	2.0338e+02 + 3.5454e+03i
38	2.0338e+02 - 3.5454e+03i
39	-4.7162e+01 + 3.6552e+03i
40	-4.7162e+01 - 3.6552e+03i
41	-8.8267e+04 + 8.4209e+04i
42	-8.8267e+04 - 8.4209e+04i
43	-8.8267e+04 + 8.4209e+04i
44	-8.8267e+04 - 8.4209e+04i
45	-1.1147e+05 + 0.0000e+00i
46	-1.1147e+05 + 0.0000e+00i

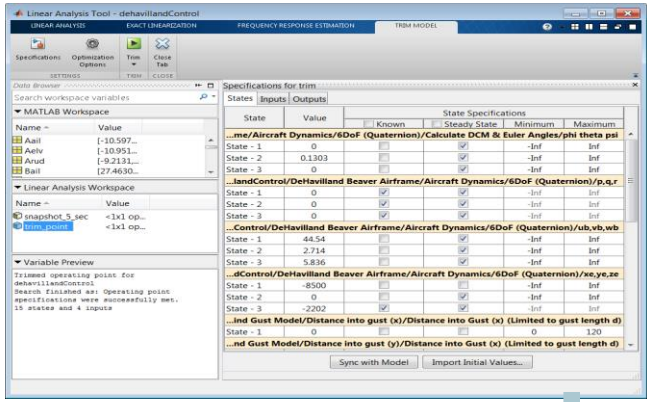
Linearization/MATLAB is accurate enough for stability analysis

04_Stability Analysis and Optimization of Complex PE System

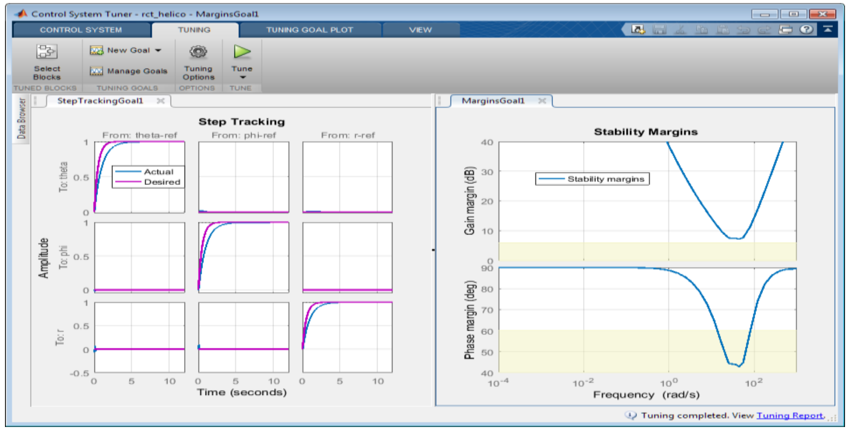
Control Design Workflow



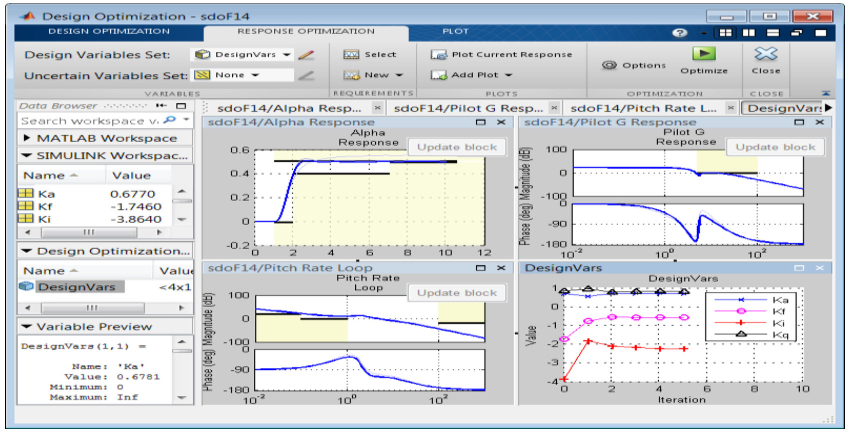
Trim and linearize



MIMO System Control Optimization:
Control System Tuner APP



Nonlinear System Control Optimization with Uncertain Parameters:
Design Optimization APP



Design and Optimize controller

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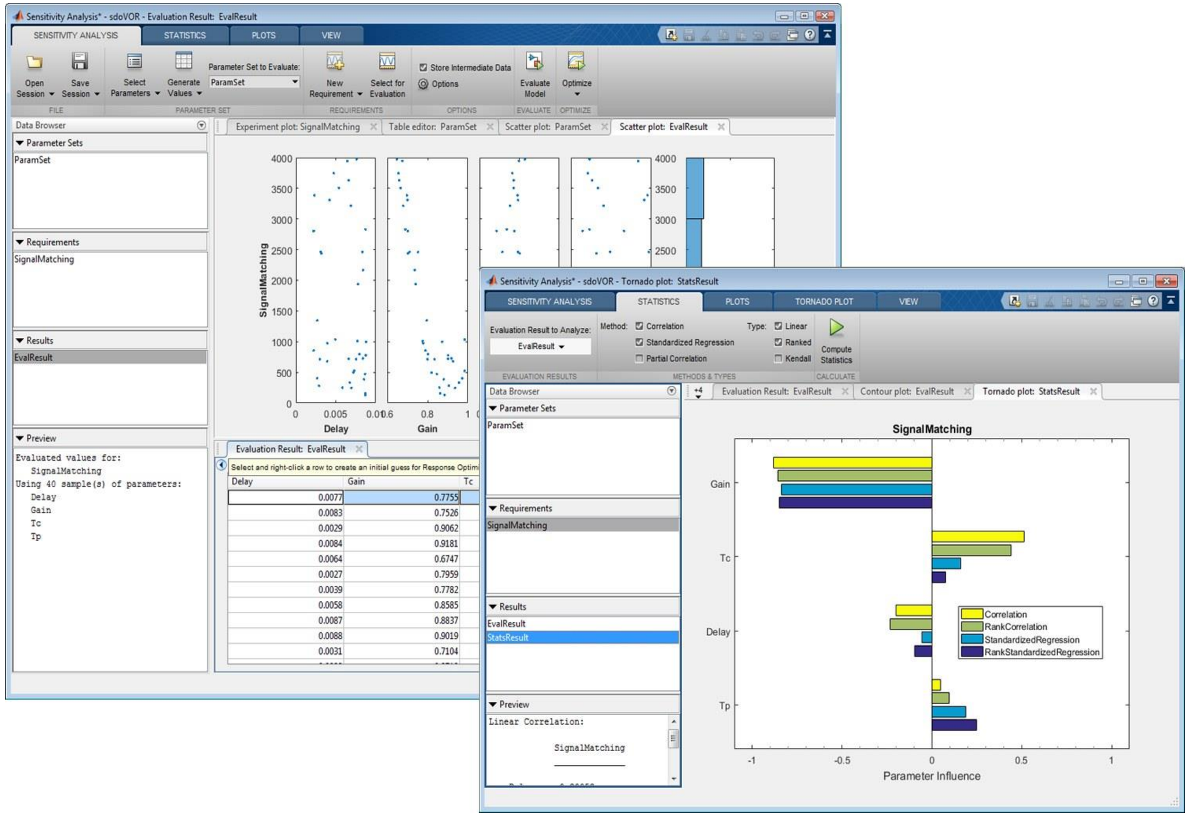
Sensitivity Analysis

- Determine the most influential parameters in the model and see how design variables affect cost function using visual and quantitative analysis
- Use Design of Experiments and Monte Carlo simulations to evaluate cost functions across the design space
- Calculate sensitivities, perform correlation analysis, and visual analysis of cost function against model parameters
- Identify good initial starting points for optimization process



Sensitivity Analysis in MATLAB is a Monte Carlo technique that simulates a model repeatedly under different parameter values

Public

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Summary on Linearization Tool in MATLAB

- Based on MATLAB, which is a General Simulation Platform
- Accurate enough for stability analysis
- Save Modeling Time
  a) Re-use the MALTAB/Simulink Model
- Save Simulation Time
  a) Faster than time domain simulation for sensitivity study with dozens of cases
- Support stability analysis of complex PE system
  a) Generate small-signal model of complex PE system
  b) further stability analysis, based on modern control theory
-

Linearization/MATLAB is recommended for stability analysis of complex PE system

05_Team Members

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Xing Huang

- Dr. Xing Huang
- Presenter's biography
  - Senior Scientist at Hitachi Energy Research, focusing on the power electronics application in power system, especially topics on power converter topologies, control and analysis.
  - Ph.D. at Beijing Jiaotong University, focusing on new energy, especially topics on grid-connected/islanding characteristics and control strategies of Microgrid, IGCT drive, PV power generation, BESS, etc.
  - IEEE member, ICEE 2014 Best Paper Award Winner
- Email
  - Helen-xing.huang@hitachienergy.com

Weichi Zhang

- Dr. Weichi Zhang
- Biography
  - Senior Scientist at Hitachi Energy Research, focusing on the renewable energy and low-carbon solutions for power transmission and distribution encompassing power converter topologies and control and analysis.
  - Ph.D. and Pos-doc Researcher at Newcastle University focusing on the power quality improvement of grid-connected converters and utilization of wide-band gap semiconductors.
  - IEEE member, IET member
- Email
  - Weichi.zhang@hitachienergy.com

Wen Jiang

- Wen Jiang
- Biography
  - Scientist at Hitachi Energy Research, focusing on control, modeling and analysis of power converters in renewable energy, power transmission and distribution.
  - M.S. degree in electrical engineering from North China Electric Power University, focusing on control and stability analysis of HVDC transmission system
- Email
  - wene-wen.jiang@hitachienergy.com

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05_Thanks to MathWorkers

Technical Support

- Lily Yan 

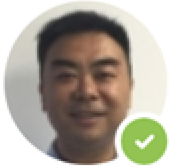
Application Engineer

- Jing Wu 
- Amy Yang 

Training Engineer

- Grace Qi 

Sales Team

- DuanWei Wang 
- Fiona Peng 

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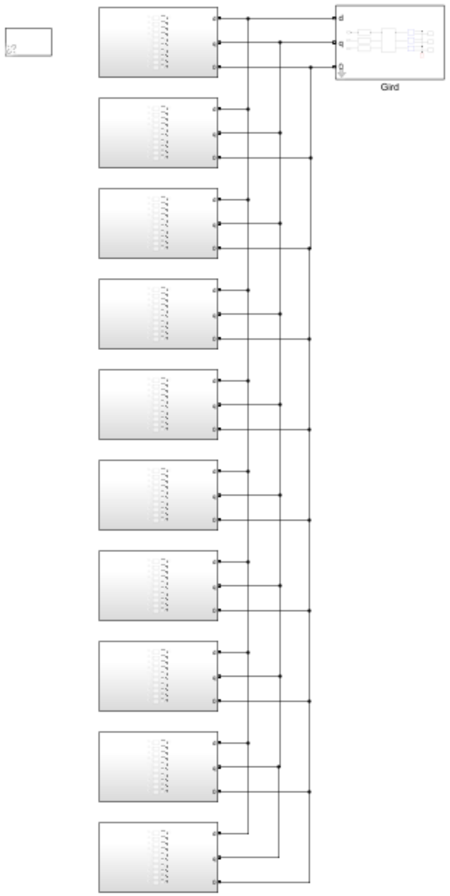
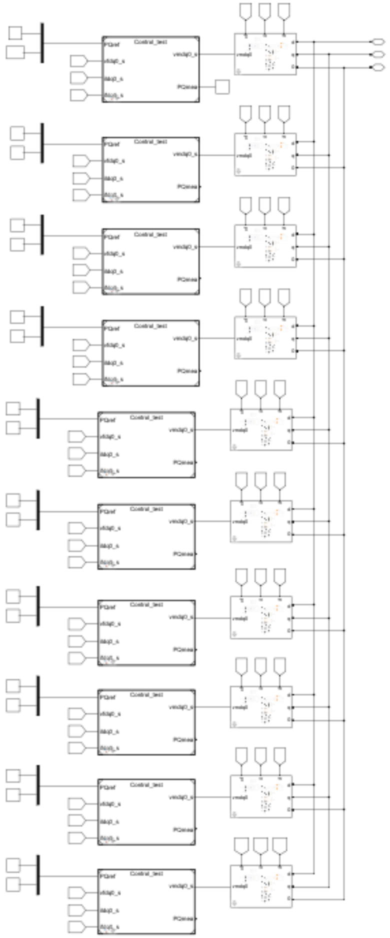
Simulation Capability: Parallel of 100 Converters

10 clusters of converters connected to PCC



10 converters in each cluster



Control Design and Optimization

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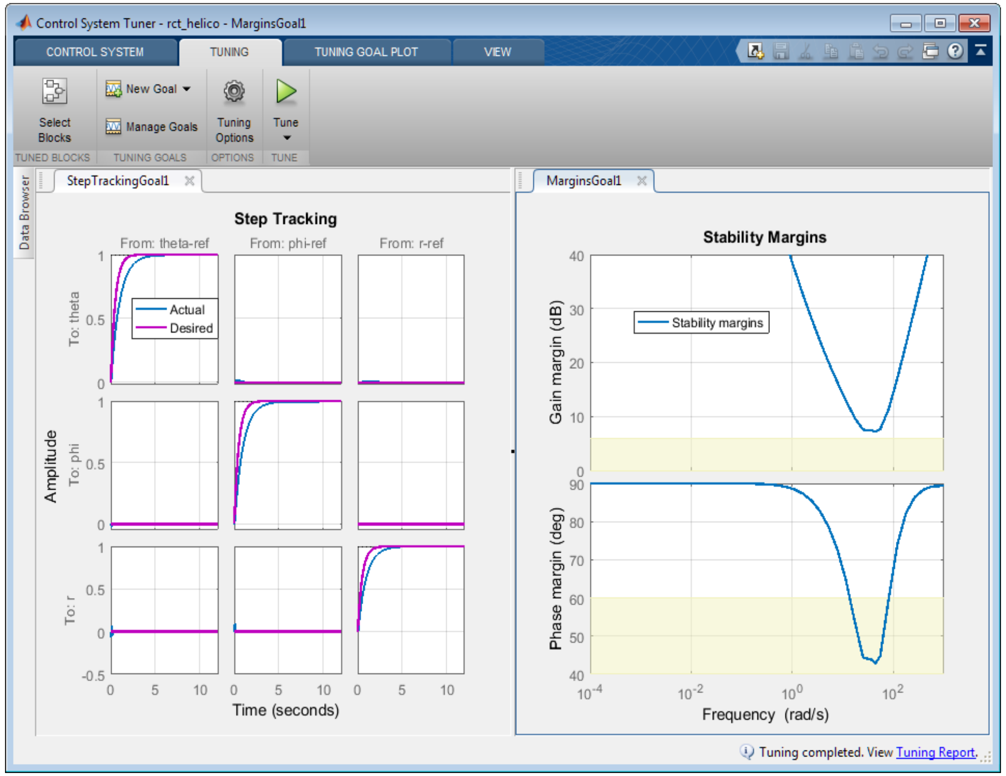
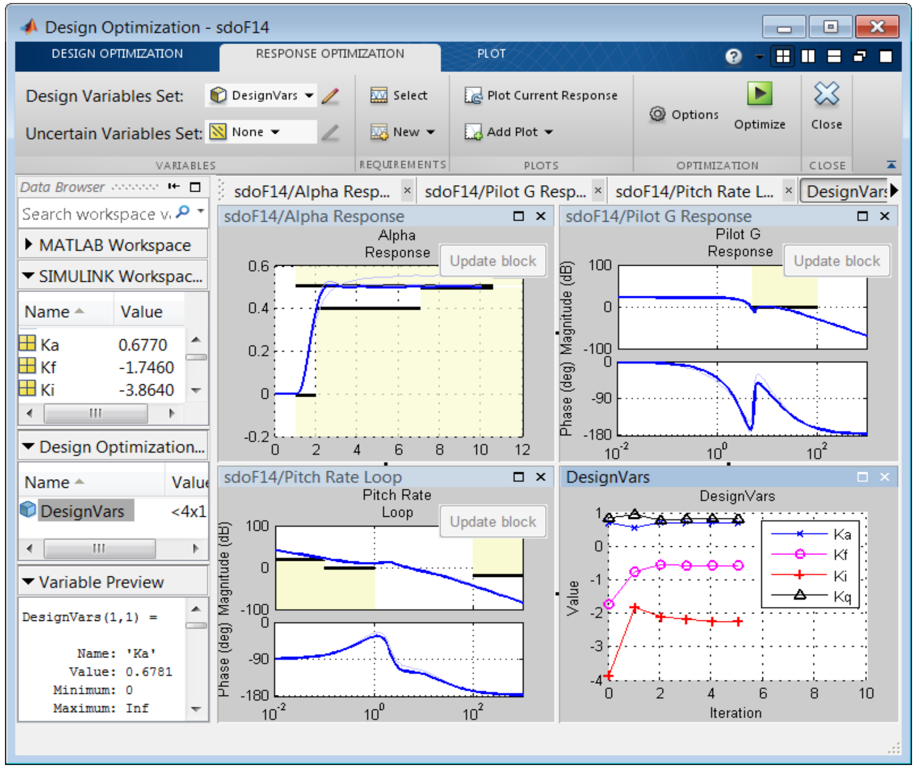
MIMO System Control Optimization



Nonlinear System Control Optimization with Uncertain Parameters



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Simulation Capability: Parallel of 100 Converters

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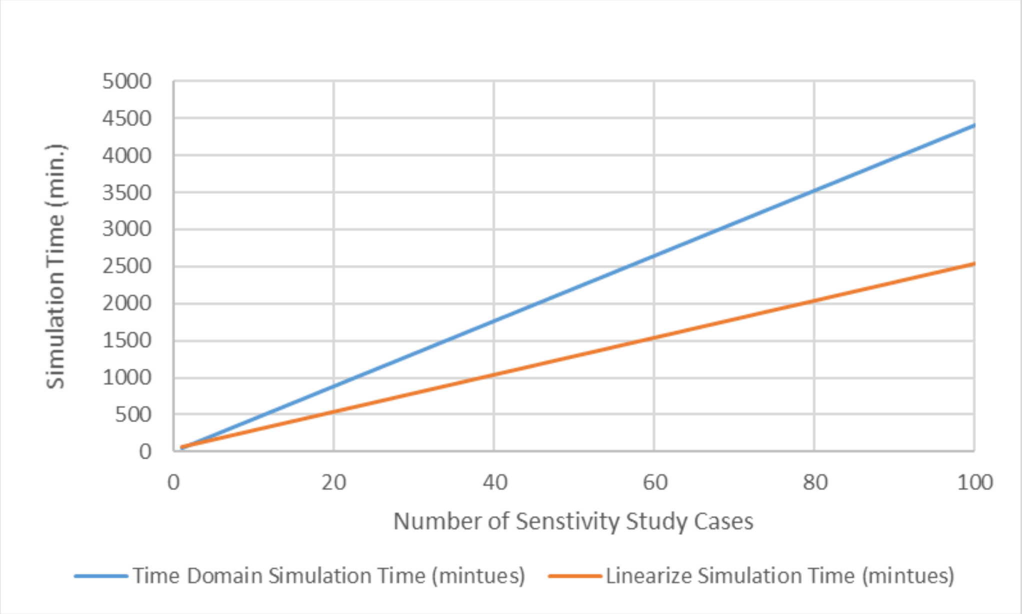
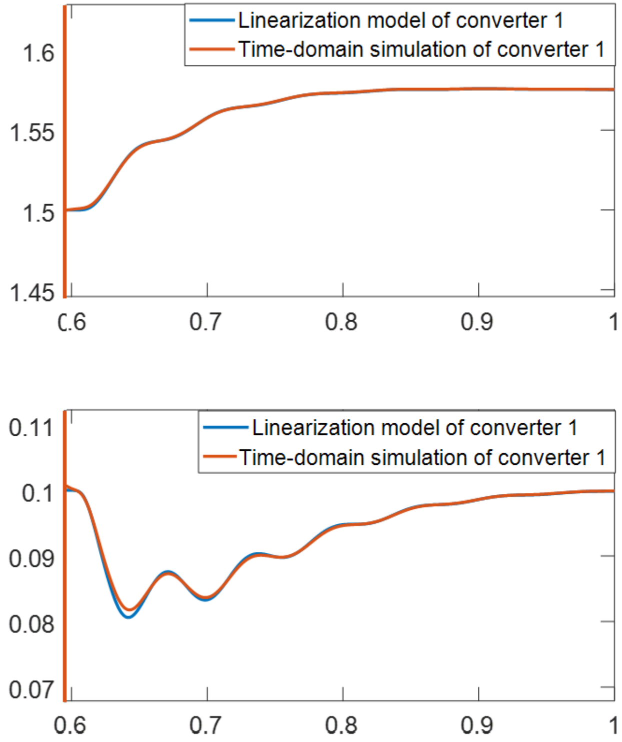
Simulation Time

- Step response waveform
  - Step change at 0.6s
  - Total simulation time 1s



Accuracy

- Step response of PQ measurement of Converter 1



Linearization/MATLAB can help to save simulation time during sensitivity study (with dozens of cases)

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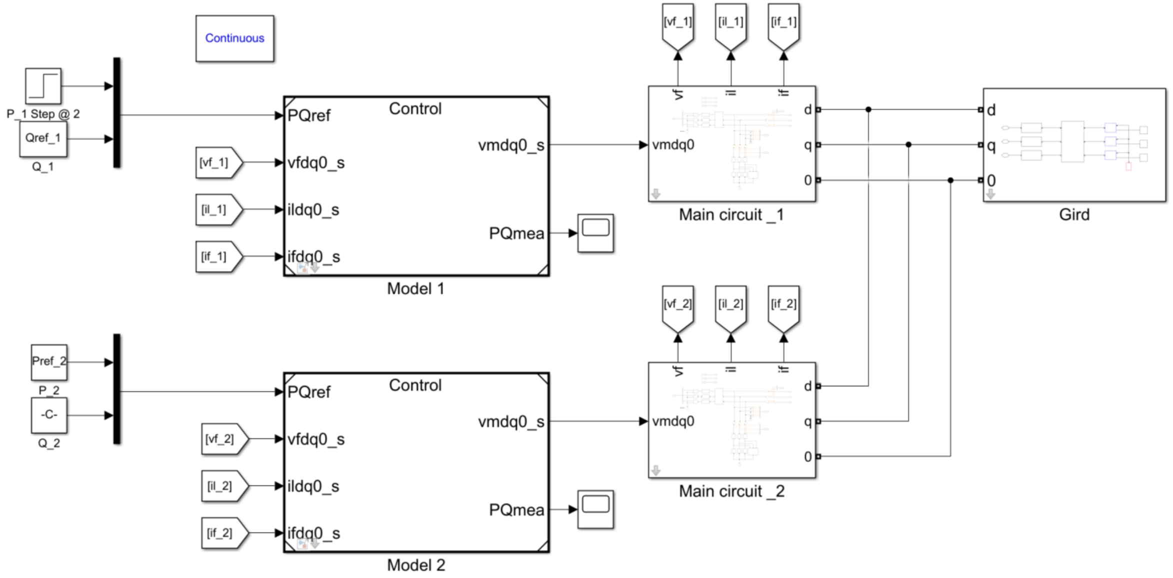
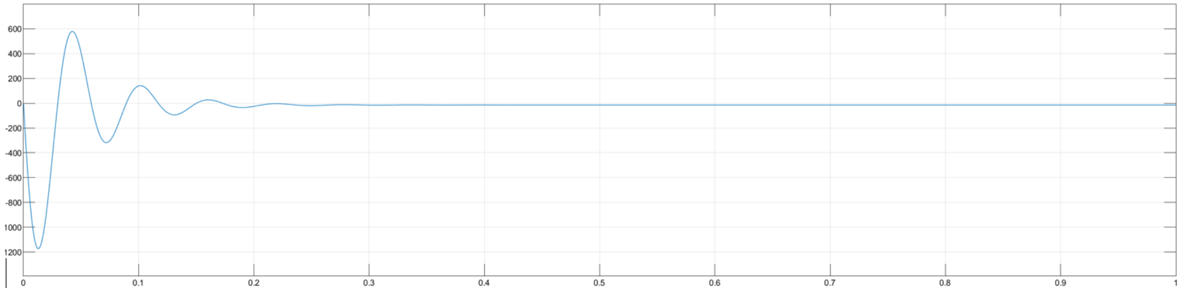
General Simulation Platform

Simulink Model





Code for Small Signal Analysis

```
clear
clc
mdl = 'CurrentLoop_LC_0220_e';
open_system(mdl)
io = getlinio(mdl);
SimTime = 1;

% Sim state name for plant
ss_plant = power_analyze(mdl,'ss');
Nx_plant1 = size(ss_plant.StateName,1);% Number of states of the plant from power_analyze()

linsys = linearize(mdl,io,SimTime);
Nx_sys = size(linsys.StateName,1);% Number of states of the whole system

i = startsWith(linsys.StateName,'state-space','IgnoreCase',true);
Nx_plant2 = nnz(i); % Number of states of the plant from linearize()

if Nx_plant2 == Nx_plant1
    linsys.StateName(i) = ss_plant.StateName;
elseif Nx_plant2 == Nx_plant1 - 3
     k = contains(ss_plant.StateName,'0');
     StateName = ss_plant.StateName(~k);
     linsys.StateName(i) = StateName;
else
    error('Number of states doesnot match')
end
```

Matrix A:

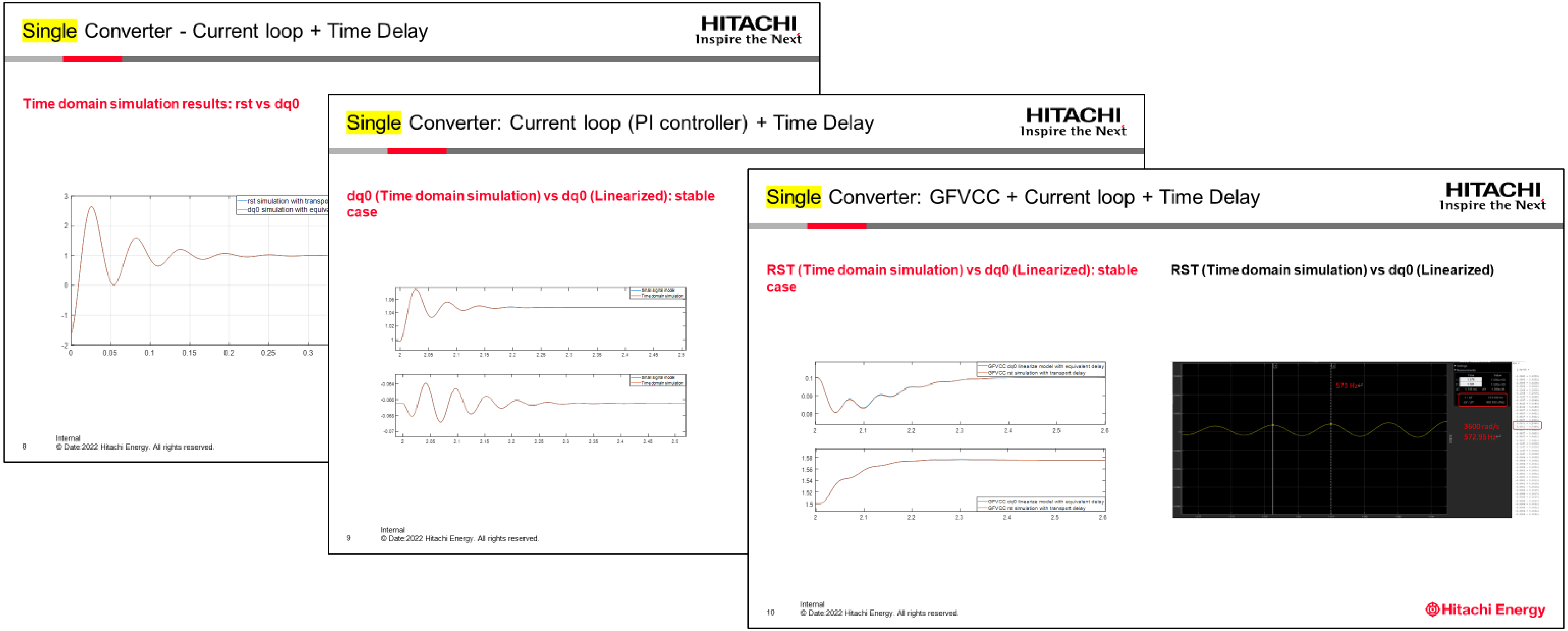
	1	2	3	4	5	6	7	8	9	10
1	0	0	314.1593	0	0	0.0844	0	94.2478	0	-0.0844
2	0	0	0	0	0	0	0	0	-0.3000	0
3	0	0	0	0	0	0.7608	0	850	0	-0.7608
4	0	0	0	0	0	0	0	0	0	-0.3000
5	4.4390e-07	3.9477e+04	0.9000	-8.5528e-08	-35.8974	314.1489	-3.8299e-07	0.2700	-11.8431	-204.0458
6	-3.5746e-08	2.7960e-08	-109.8464	3.9477e+04	-314.1487	-35.9269	2.7960e-08	-32.9539	204.0455	-11.8136
7	0	0	-0.0461	0	1.2028e+04	-1.2366e-05	0	314.1349	-1.2028e+04	1.2366e-05
8	0	0	-314.8671	0	0	1.2028e+04	-314.1487	-94.4601	0	-1.2028e+04
9	313.4686	0	-20.8782	0	4.2205	-0.0056	4.7155e+03	-6.2635	-4.2205	314.1543
10	4.7050e+03	0	-313.4897	0	0	4.1363	0	4.6214e+03	-314.1487	-4.1363

- Re-use the MALTAB/Simulink Model

- Save Modeling Time

Very Accurate

More Details



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