Adaptive Power Oscillation Damping Control via HVDC system

30th September 2021 | Webinar

Benjamin Marshall & Md Habibur Rahman
The National HVDC Centre
&
Evangelos Farantatos
Electric Power Research Institute (EPRI)

We are expecting a large number of participants to join, so the session will start a couple of minutes late.

The National HVDC Centre

EPRI | ELECTRIC POWER RESEARCH INSTITUTE

Scottish & Southern Electricity Networks
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Welcome to the Adaptive Power Oscillation Damping Control via HVDC system Webcast

The National HVDC Centre

Due to large audience, please turn off video & put microphone on mute

Questions for speaker will be managed using MS Teams chat.

This webinar may be recorded. Link to slides will be shared after the webcast.

Considering a lot of participants are expected, all questions or comments may not be addressed during the webcast. A briefing note with summary of questions, answers and technical discussions will be published and circulated to all participants after the webinar.

Expected audience from

- ● Electricity Utility / System Operator
- ● Project Developer / Equipment Manufacturer
- ● Research, Development & Innovation
- ● Advisory / Consulting
- ● Others

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Agenda

Time	Description
16.00 - 16:05	Welcome and Context Setting
16.05 - 16:45	Adaptive Power Oscillation Damping Control via HVDC system
16:45 – 16:50	Adaptive POD applied to HVDC and other large Power Electronic converters
16:50 – 17:00	Q&As

☐ **Speakers:**

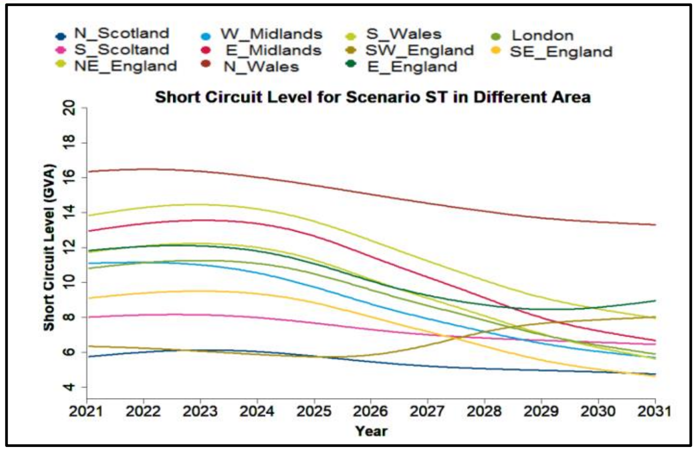
  ○ **Evangelos Farantatos -Electric Power Research Institute (EPRI)**

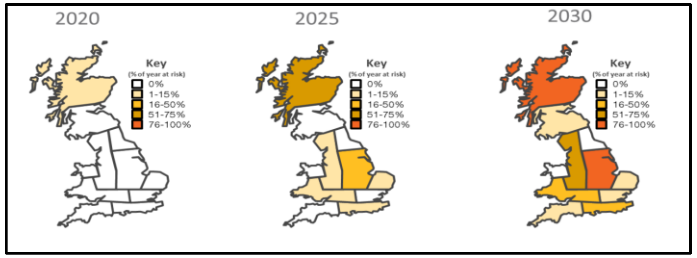
  ○ **Benjamin Marshall – The National HVDC Centre**

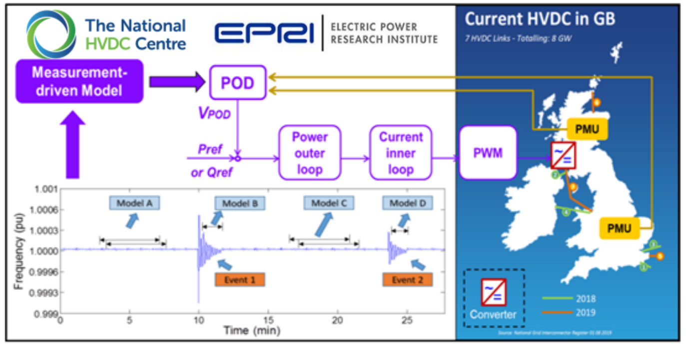
☐ **Moderator:**

  ○ **Md Habibur Rahman – The National HVDC Centre**

Key Drivers for POD Control via HVDC system







- ○ The increased integration of renewable sources and HVDC transmission links is significantly changing the characteristics of the Great Britain (GB) grid.
- ○ Reduced system inertia, declining Short-circuit level and frequent operating condition variations in the GB network, could potentially lead to oscillations across a wide frequency range.
- ○ In 2020, the National HVDC Centre awarded Electric Power Research Institute (EPRI) to design adaptive power oscillation damping (POD) controllers via HVDC to support de-risking of HVDC projects in the GB.
- ○ Accurate assessment of potential POD implementation is critical for ensuring stable operation of future and evolving Power system network.

Adaptive Power Oscillation Damping Control via HVDC System

Evangelos Farantatos
Electric Power Research Institute (EPRI)

Benjamin Marshall & Md Habibur Rahman
The National HVDC Centre

September 30, 2021

Acknowledgements

The National HVDC Centre

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- Md Habibur Rahman
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THE UNIVERSITY OF TENNESSEE KNOXVILLE

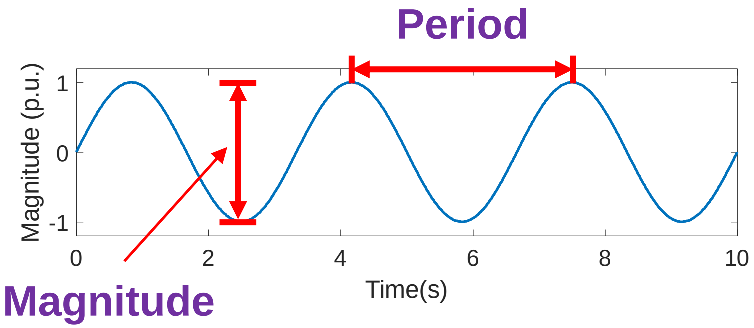
- Yi Zhao
- Yuqing Dong
- Kaiqi Sun
- Khaled Alshuaibi
- Chengwen Zhang
- Lin Zhu (now with EPRI)
- Yilu Liu

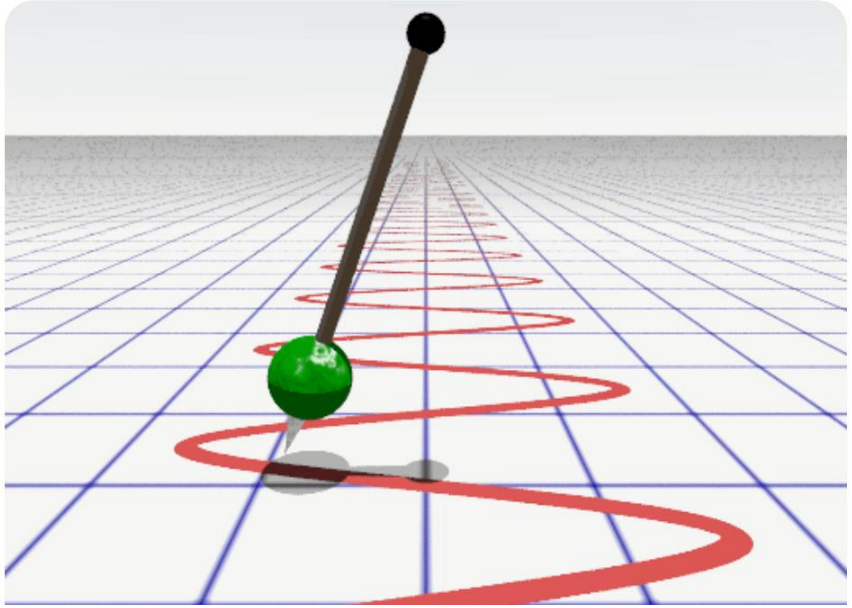
Outline

- Background and Motivation
- Modal Analysis of GB Power Grid Model
- POD Design and Performance Assessment in PowerFactory
- Software POD Controller in RTDS
- Hardware POD Controller Implementation and Hardware-In-the-Loop Testing
- Adaptive POD Performance
- Sub-Synchronous Oscillation (SSO) Mitigation
- Summary

Oscillations

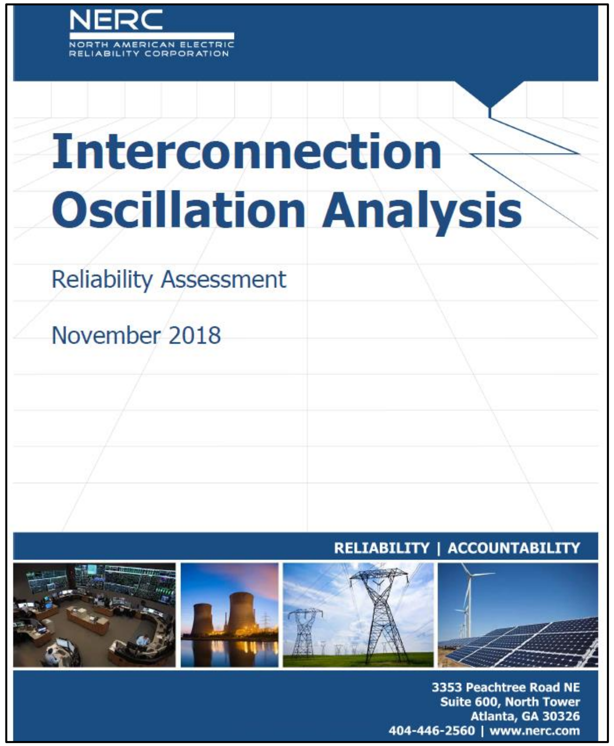
Electromechanical oscillations: inherent property of power systems





Source: Google

US



NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

Interconnection Oscillation Analysis

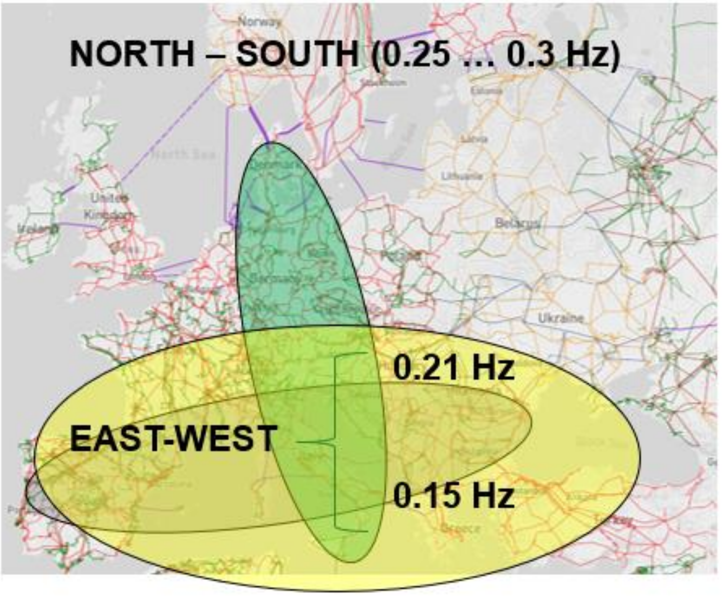
Reliability Assessment

November 2018

RELIABILITY | ACCOUNTABILITY

3353 Peachtree Road NE
Suite 600, North Tower
Atlanta, GA 30326
404-446-2560 | www.nerc.com

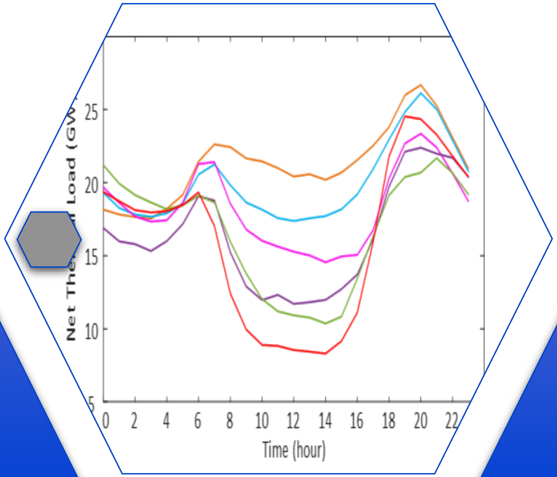
Continental Europe



Grid Transformation

Variability & uncertainty in generation & demand → frequently varying oscillation modes, dependent on the operating condition

Retiring fuel-based generation → insufficient stabilizing capability



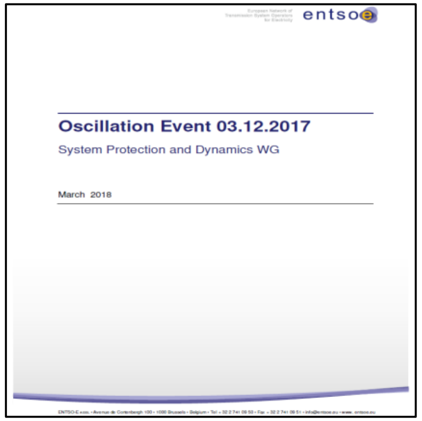
Increasing inverter- based generation → new system dynamics & stability properties

Large number of controllable devices including HVDC

Oscillations Events

Low Frequency Oscillations

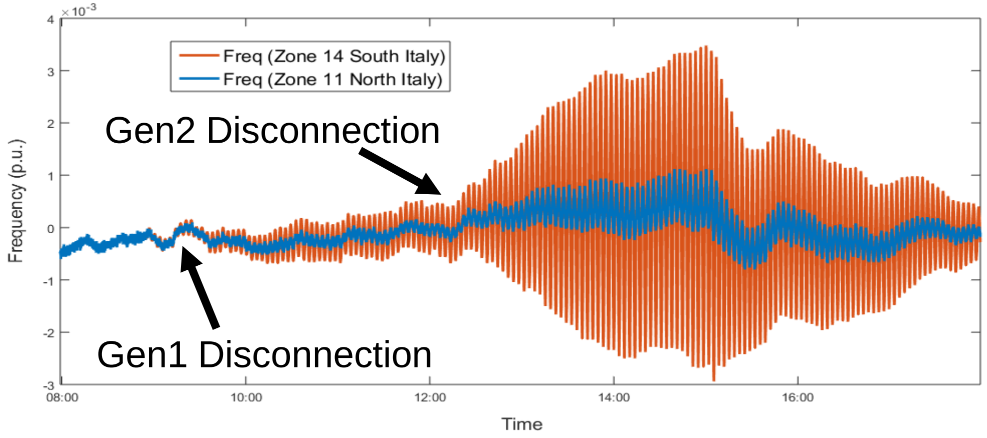
- EU Events
  - Dec 3rd 2017 (0.29 Hz)
  - Dec 1st 2016
  - February 19th & 24th 2011


entsoe

Oscillation Event 03.12.2017

System Protection and Dynamics WG

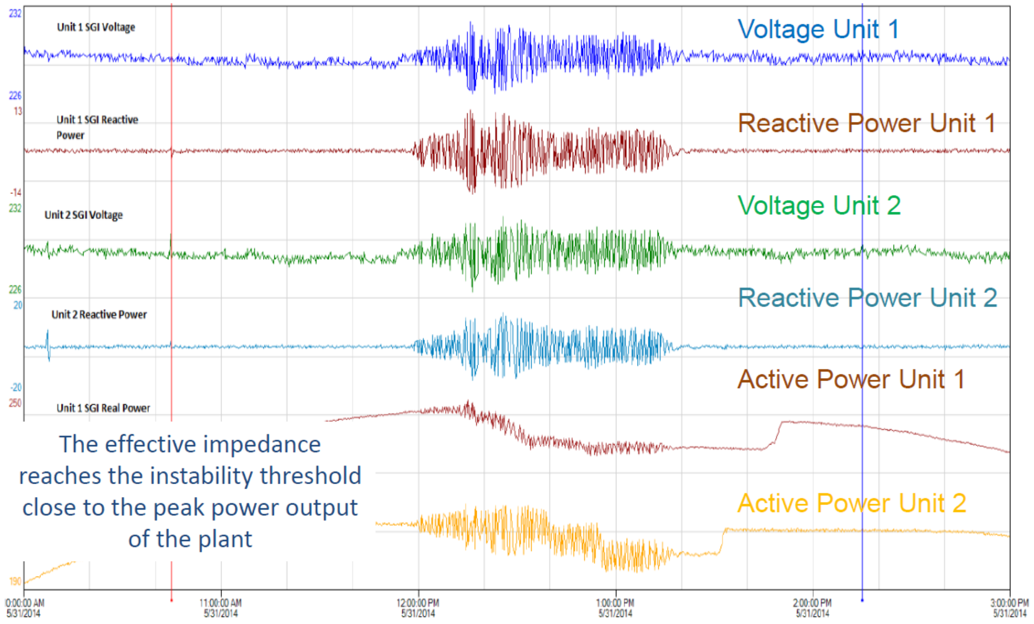
March 2018



Sub-Synchronous Oscillations

- Inverter controls might create sub-synchronous oscillations (typically 5.0-15.0 Hz) due to control interactions and/or network resonance

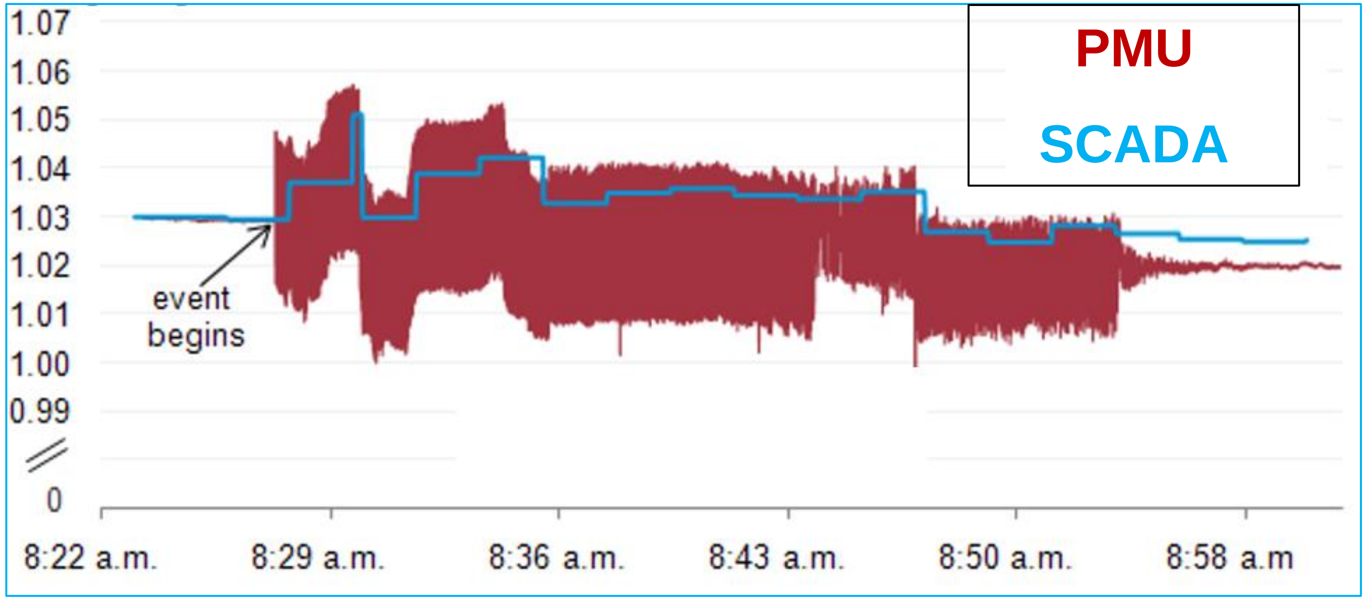
PV Plant – ~7 Hz Oscillation

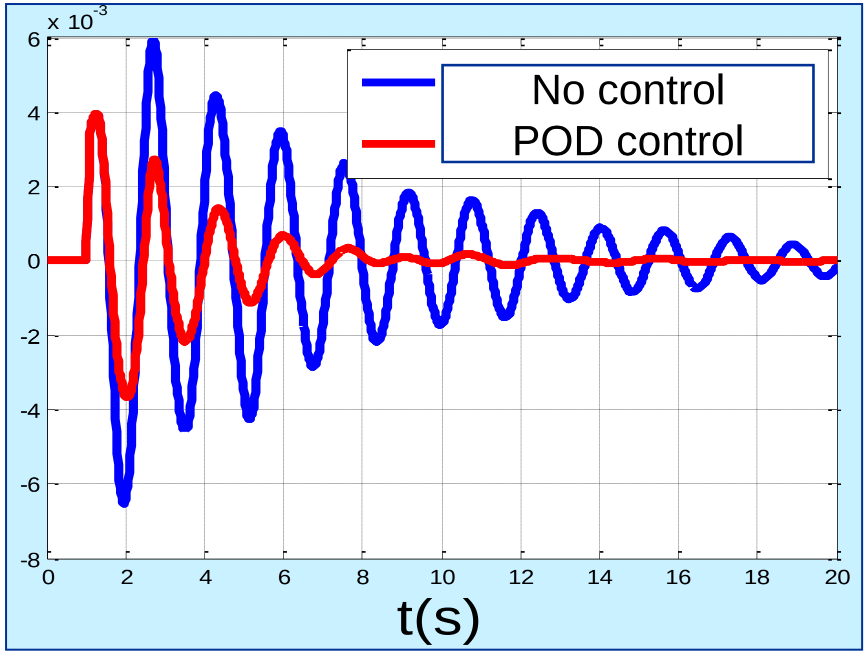


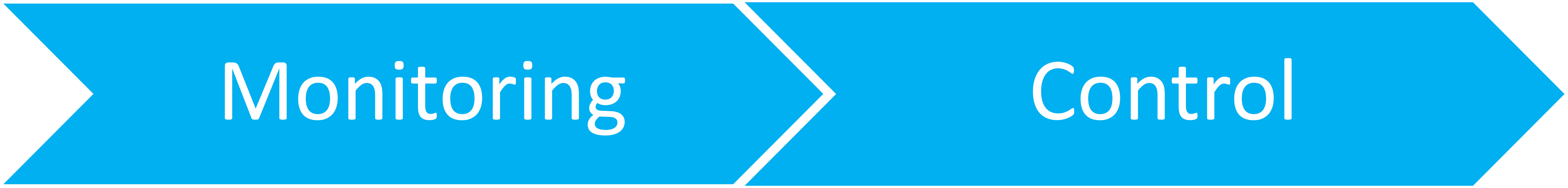
The effective impedance reaches the instability threshold close to the peak power output of the plant

First Solar Inc., "Deploying utility-scale pv power plants in weak grids," in *2017 IEEE Power & Energy Society General Meeting*, Jul. 2017.

Synchrophasor Technology for Oscillations Monitoring & Control





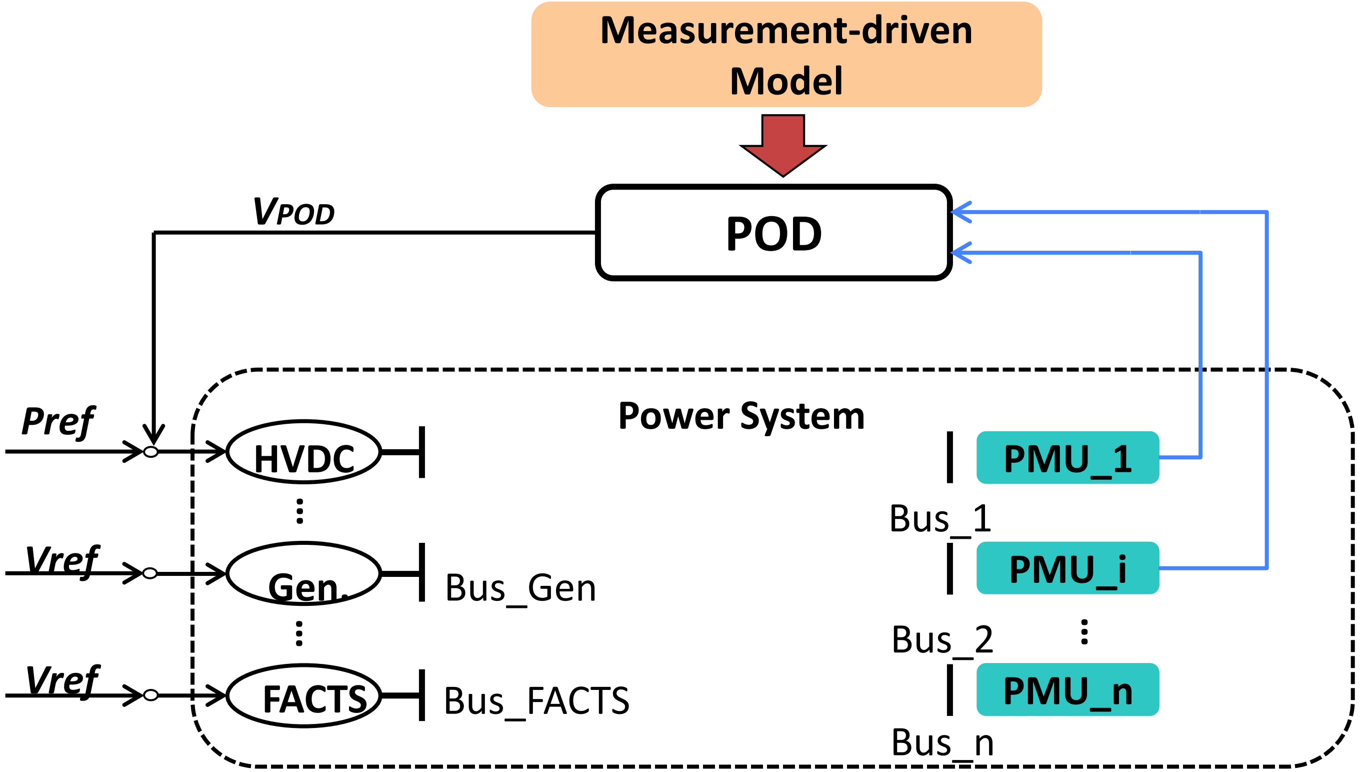


Monitoring

Control

Adaptive Power Oscillation Damping Control

Objective: Develop adaptive Power Oscillation Damping (POD) controllers to mitigate low frequency inter-area oscillations & local sub-synchronous oscillations



Tasks

	Task
1	Modal analysis of GB power grid
2	Optimal observation signal and actuation signal selection for POD controller implementation at the GB power grid
3	Simulation-based performance evaluation of adaptive POD controller using measurement-driven model for GB power grid
4	Controller implementation and hardware-in-the-loop testing on RSCAD/RTDS
5	Impact of measurement latency and data package loss on performance of POD controller for GB power grid implementation
6	POD controller with backup PMU channels and backup actuators for GB power grid implementation

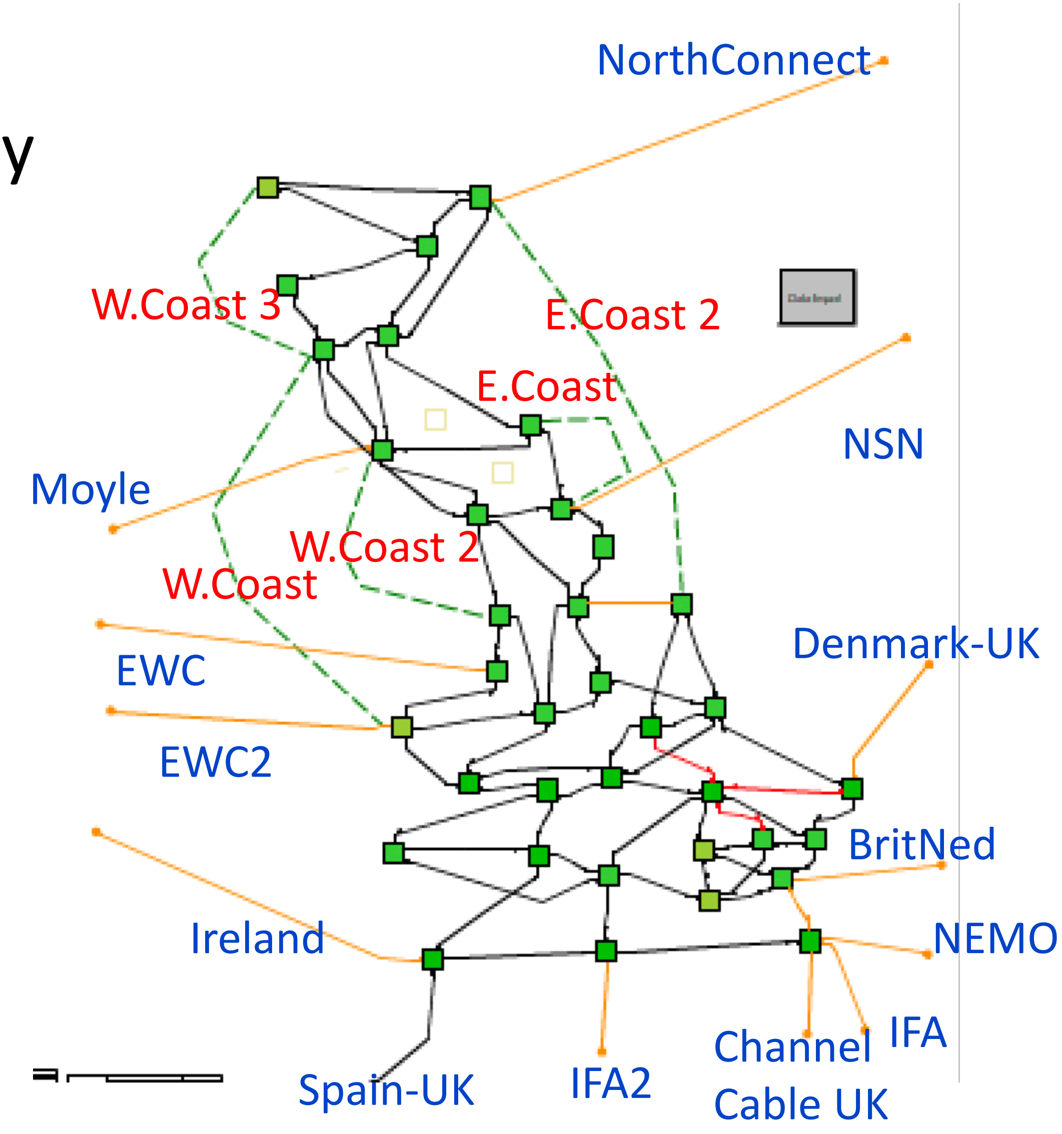
Simulations in PowerFactory (Tasks 1–3)

Hardware controller implementation and RTDS Hardware-in-the-Loop testing (Tasks 4–6)

36 Bus GB Power Grid Model

- Reduced 36-bus GB grid model in PowerFactory
- 13 international and 5 domestic HVDC links
- Representing renewable dominated grid
- Developed by National Grid ESO

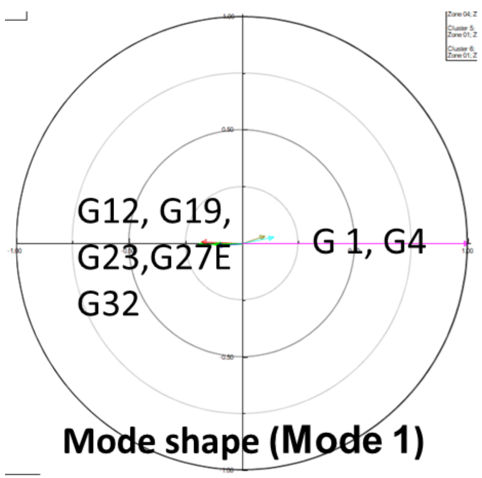
HVDC	Technology	Terminal 1	Terminal 2	Capacity (MW)
W.Coast	LCC	Z19	Z28	3000
W.Coast 2	VSC	Z22	Z27W	5000
W.Coast 3	VSC	Z28	Z32	5000
E.Coast	VSC	Z25	Z27E	3000
E.Coast 2	VSC	Z24	Z33	5000



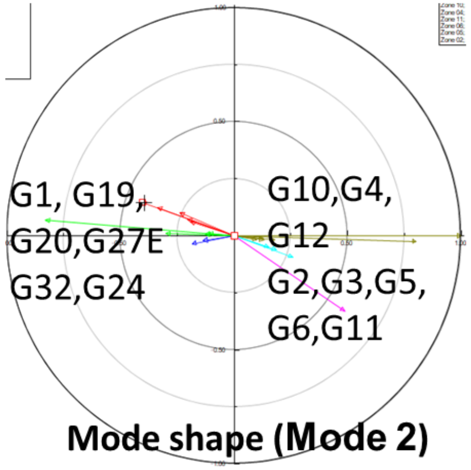
Modal Analysis of GB Power Grid Model

Modal Analysis of GB Power Grid Model

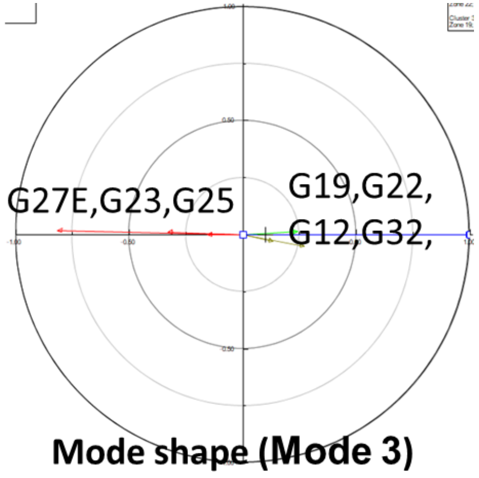
- Three dominant oscillation modes:
  - Mode #1: North vs. South (0.8796 Hz, 3.27%)
  - Mode #2: South-East vs. west (1.0148 Hz, 7.81%)
  - Mode #3: Local (1.4167 Hz, 8.15%)
- Modes verified through dynamic simulations



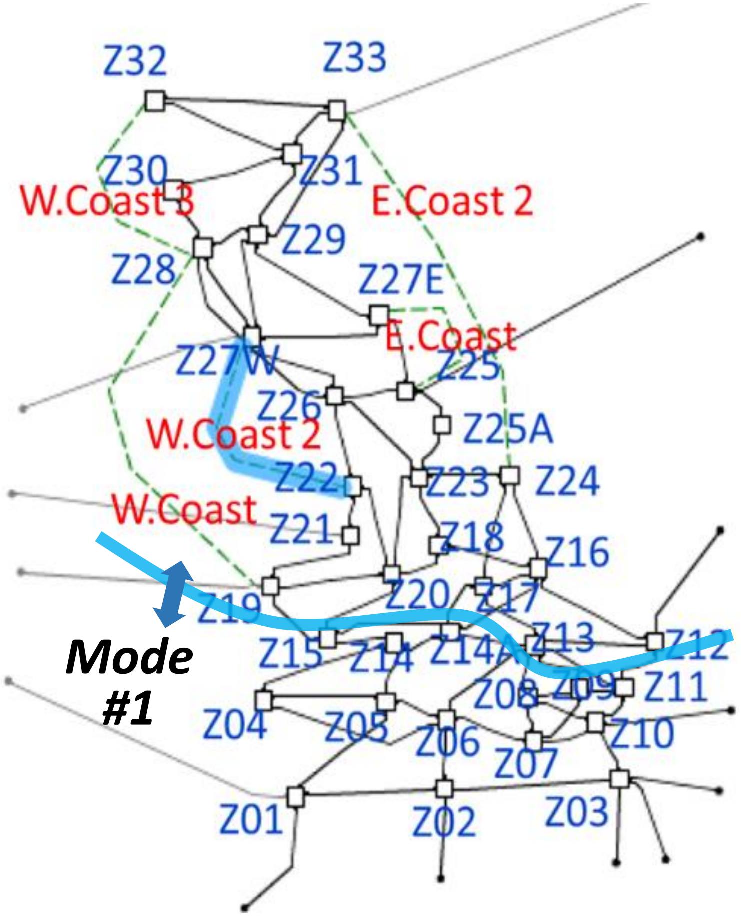
Mode shape (Mode 1)



Mode shape (Mode 2)

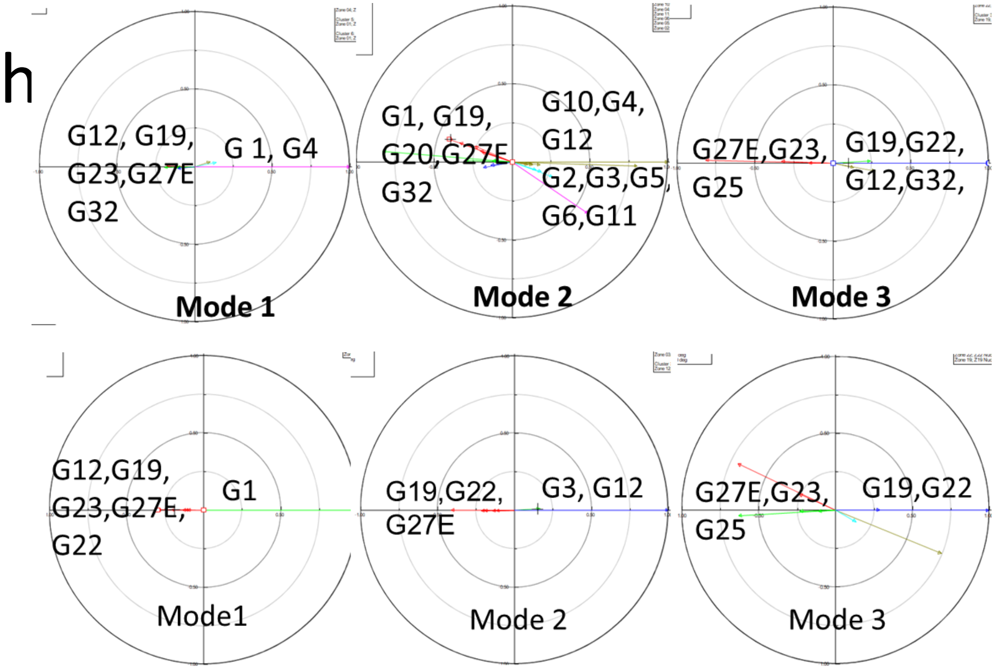


Mode shape (Mode 3)



Modal Analysis Under Different Dispatch Scenarios

- Modal analysis under scenarios with varying demand power and wind/solar generation
- Varying oscillation frequency, damping ratio, and mode shape under different dispatches

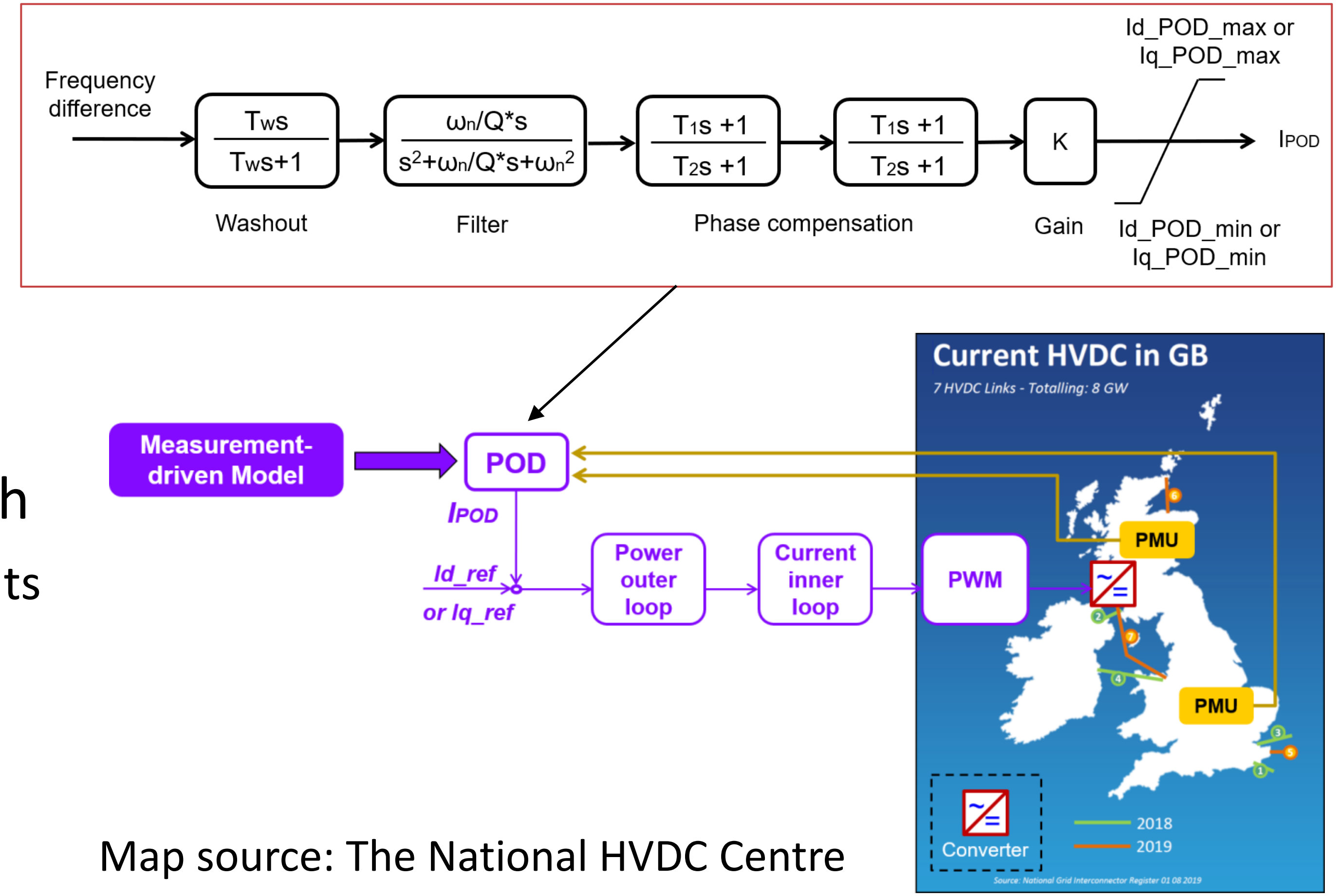


Dispatch					Mode 1		Mode 2		Mode 3	
Description		Demand power(GW)	Wind (GW)	Solar (GW)	Freq. (Hz)	Damp. Ratio (%)	Freq. (Hz)	Damp. Ratio (%)	Freq. (Hz)	Damp. Ratio (%)
High Demand	Day	50	5	10	0.7362	3.48	0.8325	5.22	0.8497	5.61
	Night	50	15	0	0.7337	3.35	0.8310	5.18	0.8476	5.48
Intermediate Load	Day	40	15.5	8.5	0.8796	3.27	1.0148	7.81	1.4167	8.15
	Night	40	24	0	0.8790	3.29	1.0144	7.80	1.4165	8.20
Low load	Day	35	10	15	0.9481	2.64	1.2147	5.68	1.3862	7.41
	Night	35	25	0	0.9417	2.42	1.2055	5.42	1.3874	7.35

POD Design and Performance Assessment in PowerFactory

POD Design Based on Measurement-Driven Model

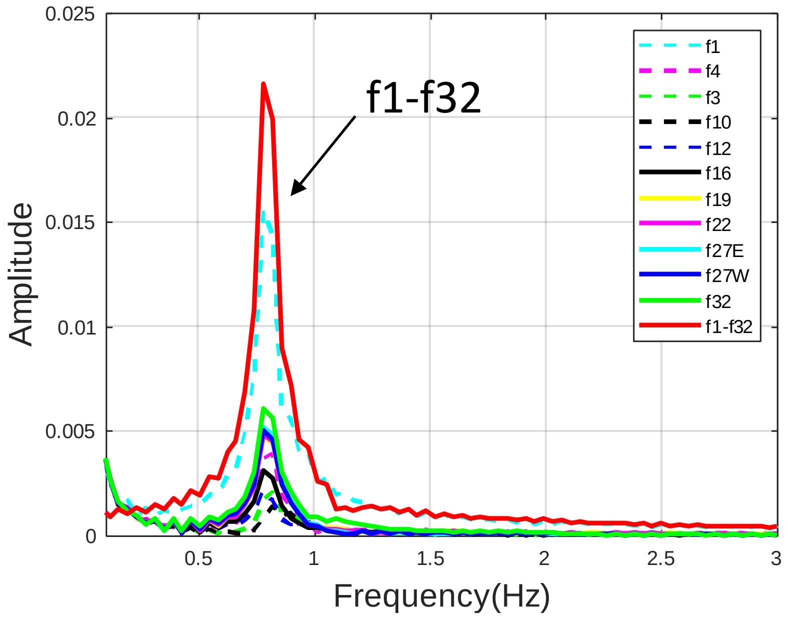
- Target mode: Mode 1 (0.879Hz, 3.27%)
- POD: lead-lag structure, washout, filter, gain, and limiter
- Observation/feedback signal: Bus frequency or frequency difference
- Actuator: VSC-HVDC links via P modulation, Q modulation, or P&Q modulation
- Measurement-driven Model Approach
  - Using ambient or ring-down measurements to build a transfer function model, and adjust the POD parameters to make it adaptive



Map source: The National HVDC Centre

Optimal Observation/Feedback Signal Selection

- FFT analysis was used to select the optimal observation/feedback signal
  - Frequency difference between Bus 1 and Bus 32 was selected (f1 - f32)



FFT analysis result in Event 1

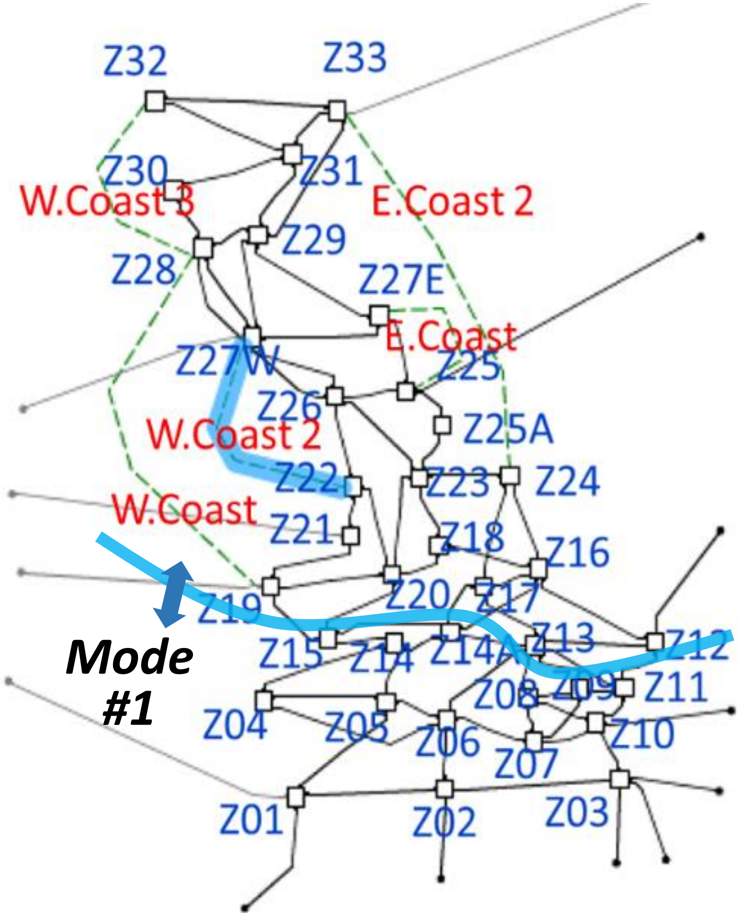
Normalized Observability Index

Area	Signal	Fault at Line 26-27E (Event 1)	Fault at Line 1-5 (Event 2)	Fault at Line 15-19 (Event 3)	Fault at Line 12-16 (Event 4)	Mean
England	f_1	0.657887	0.59663	0.65813	0.659855	0.643125
	f_4	0.369368	0.532998	0.379102	0.314503	0.398993
	f_3	0.106626	0.11378	0.106661	0.122574	0.11241
	f_10	0.068499	0.076851	0.080225	0.082348	0.076981
	f_12	0.115328	0.135261	0.104049	0.118304	0.118235
	f_16	0.185765	0.220187	0.180509	0.189404	0.193966
	f_19	0.277702	0.329063	0.276558	0.248978	0.283075
	f_22	0.282997	0.335718	0.282035	0.258035	0.289696
Scotland	f_27E	0.301845	0.356955	0.294705	0.292874	0.311595
	f_27W	0.291891	0.345748	0.286847	0.282763	0.301812
	f_32	0.347884	0.410938	0.345389	0.340166	0.361094
Frequency difference	f_1-f_32	1	1	1	1	1

Optimal Actuator Selection

- Residue method was used to select the optimal actuator
- The four VSC-HVDC links were candidate actuators

HVDC	Terminal 1	Terminal 2	Type	Capacity (MVA)	Residue (Normalized)
W.Coast 2	Z22	Z27W	VSC-HVDC	5000	0.55
W.Coast 3	Z28	Z32	VSC-HVDC	5000	1.00
E.Coast	Z25	Z27E	VSC-HVDC	3000	0.88
E.Coast 2	Z24	Z33	VSC-HVDC	5000	1.00

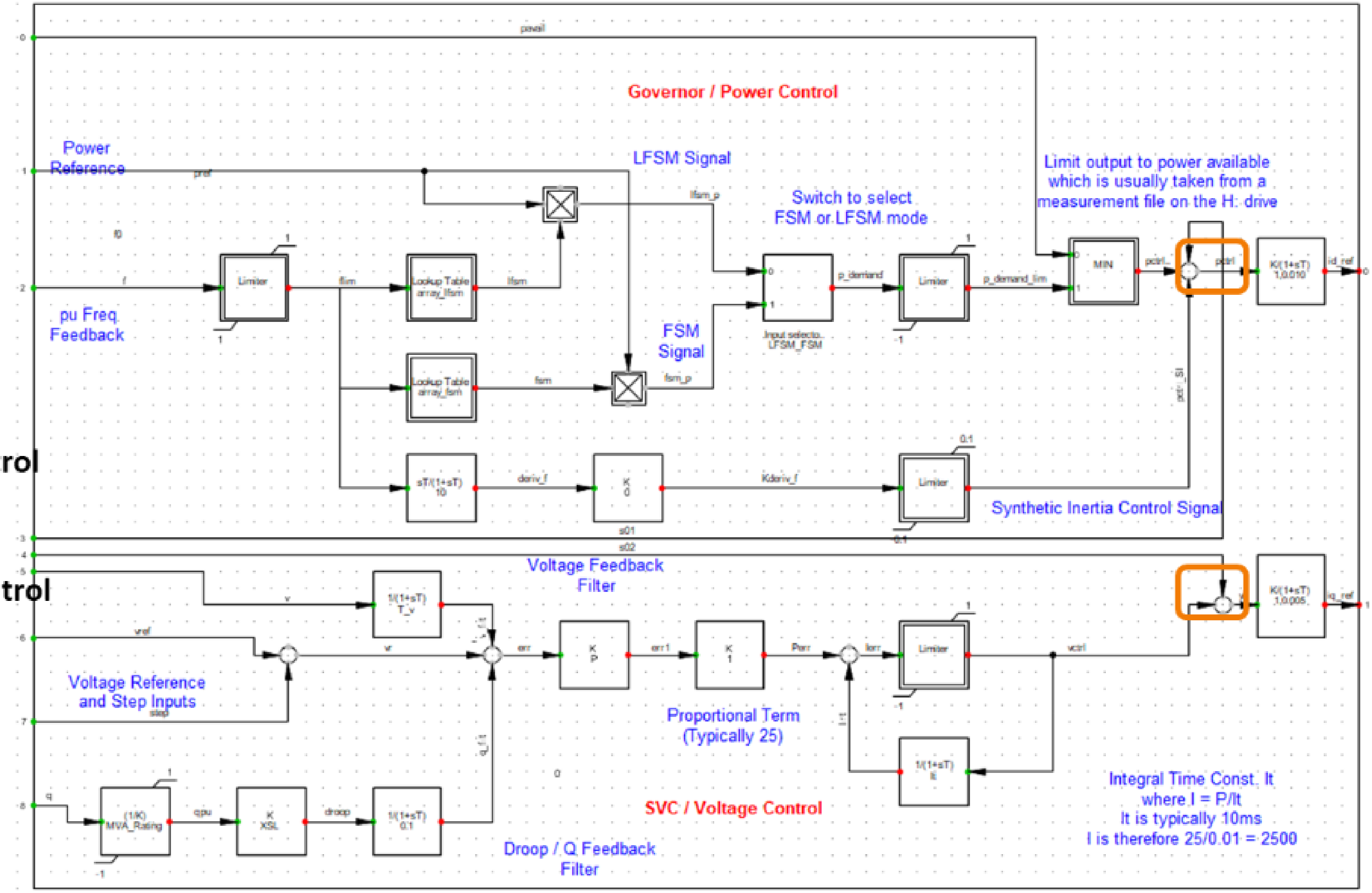


POD Implementation in PowerFactory

- POD control command was added to id_ref and iq_ref

Active power control command

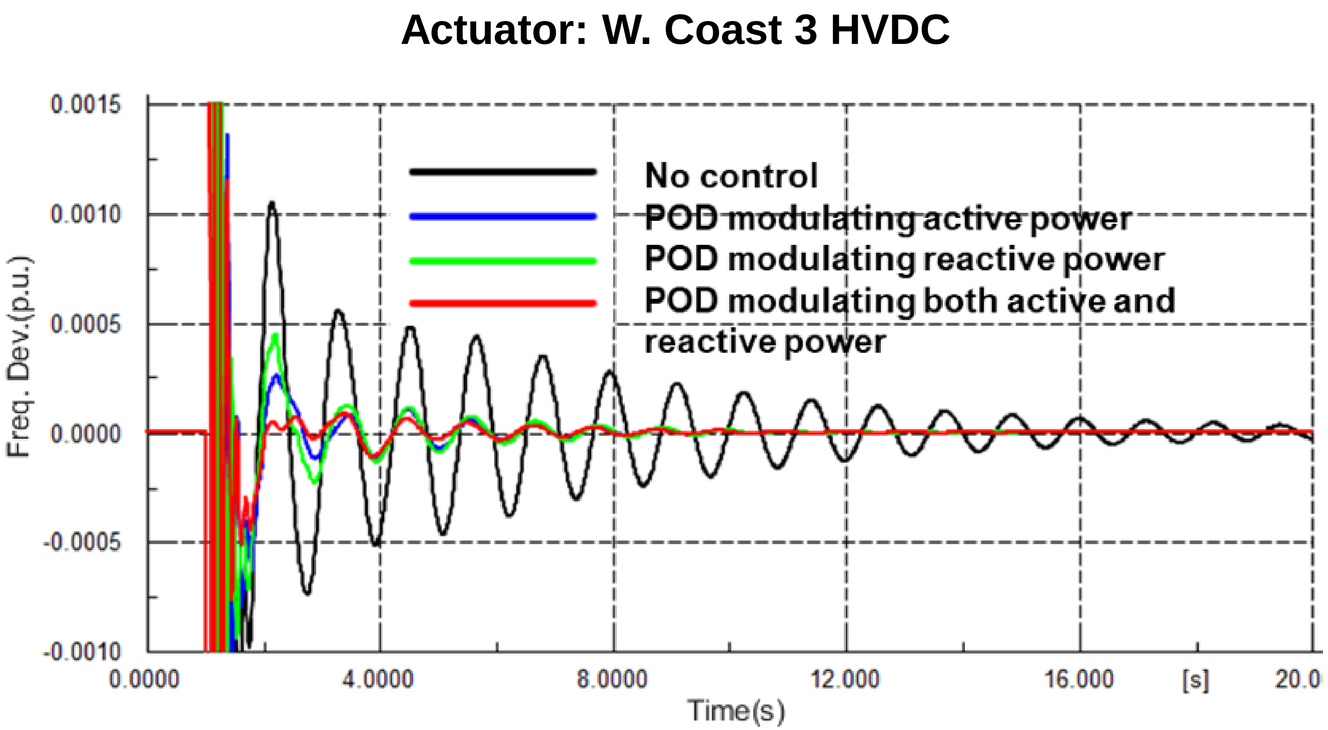
Reactive power control command



HVDC control signal Id_ref with POD control command

HVDC control signal Iq_ref with POD control command

POD Performance in PowerFactory


Actuator: W. Coast 3 HVDC

HVDC	Scenario	Frequency (Hz)	Damping ratio (%)
W. Coast 3	No control	0.87	3.3
	POD modulating P	0.92	9.1
	POD modulating Q	0.91	7.0
	POD modulating P&Q	1.01	12.5
E. Coast 2	No control	0.87	3.3
	POD modulating P	0.93	8.7
	POD modulating Q	1.01	7.5
	POD modulating P & Q	1.00	>15
W. Coast 2	No control	0.87	3.3
	POD modulating P	0.94	8.7
	POD modulating Q	0.90	7.2
	POD modulating P & Q	1.30	13.1
E. Coast	No control	0.87	3.3
	POD modulating P	0.89	7.1
	POD modulating Q	0.91	7.0
	POD modulating P & Q	0.95	10.1

- POD on VSC-HVDC links by P, Q, and P&Q modulation
- P modulation more effective than Q modulation
  - However P modulation is limited to 10% capacity
- P&Q modulation more effective than individual P or Q

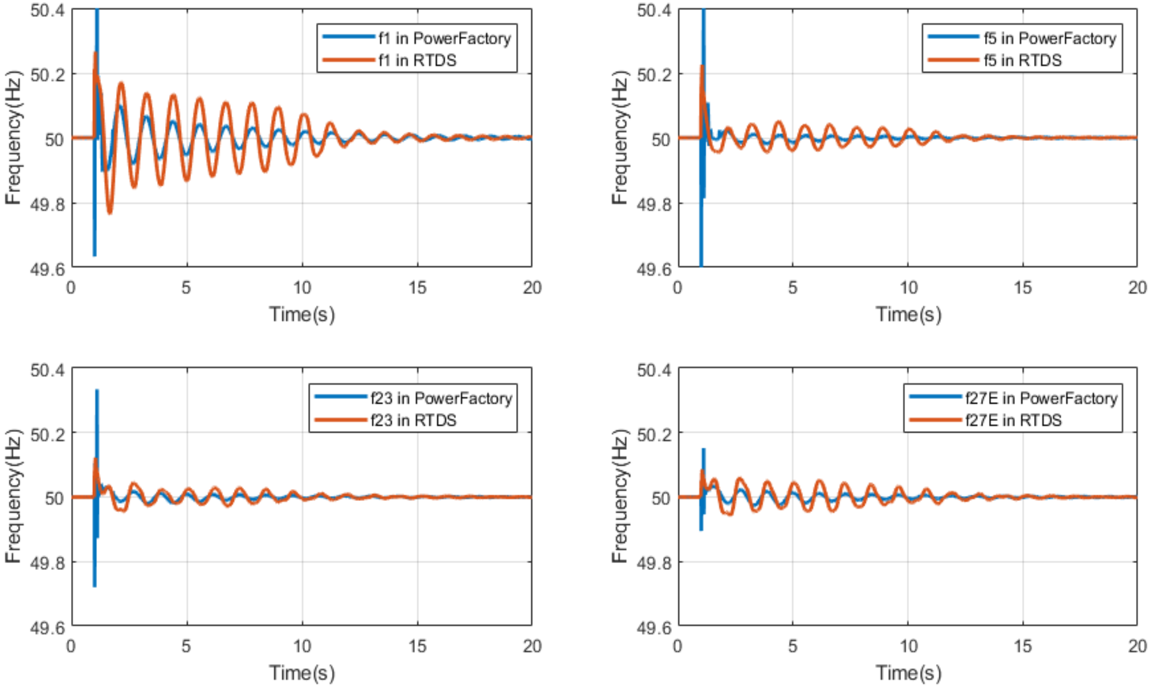
Software POD Controller in RTDS

PowerFactory Model Conversion to RTDS Model

Power Flow

HVDC	Zone	Variable	PowerFactory	PSS/e	RTDS
E. Coast 2	Zone 33	Voltage magnitude/pu	1.0080	1.0084	1.0102
		Voltage angle/deg	37.78	38.36	35.38
	Zone 24	Voltage magnitude/pu	1.0084	1.0069	1.0069
		Voltage angle/deg	12.20	12.28	9.97
W. Coast 3	Zone 32	Voltage magnitude/pu	1.0243	1.0288	1.0303
		Voltage angle/deg	47.40	47.96	44.85
	Zone 28	Voltage magnitude/pu	1.0132	1.0137	1.0157
		Voltage angle/deg	29.87	30.35	27.50

Dynamic Response



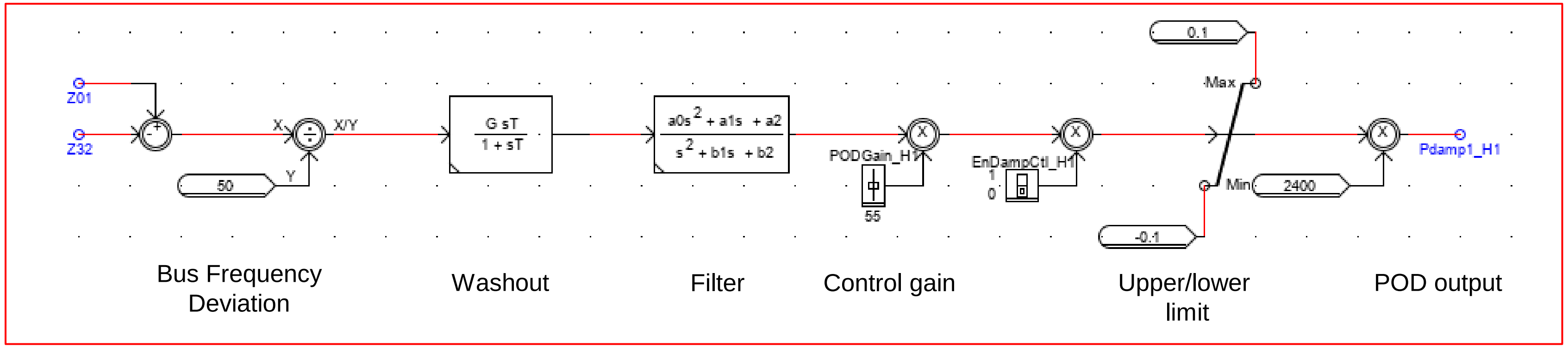
Modal Analysis

Model			Oscillation Frequency (Hz)	Damping Ratio(%)
PowerFactory	Small signal analysis tool		0.880	3.27
RTDS	Line fault	Zone 02	0.890	3.94
		Zone 21	0.890	3.32
		Zone 27W	0.890	3.11
	Generator trip	Zone 02	0.922	2.60
		Zone 25	0.929	3.43

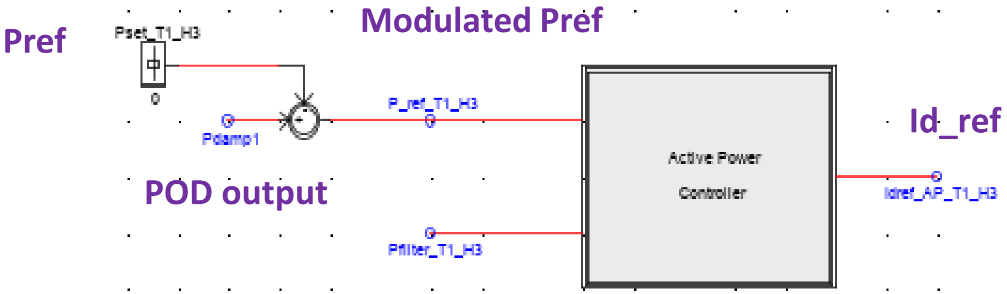
- Converted PowerFactory model to RSCAD format with detailed VSC-HVDC link models for real-time simulation on RTDS
- Focused on matching oscillation modes
- Good match in power flow and dynamic response
  - Some differences due to user defined models in PowerFactory and detailed HVDC models in RTDS

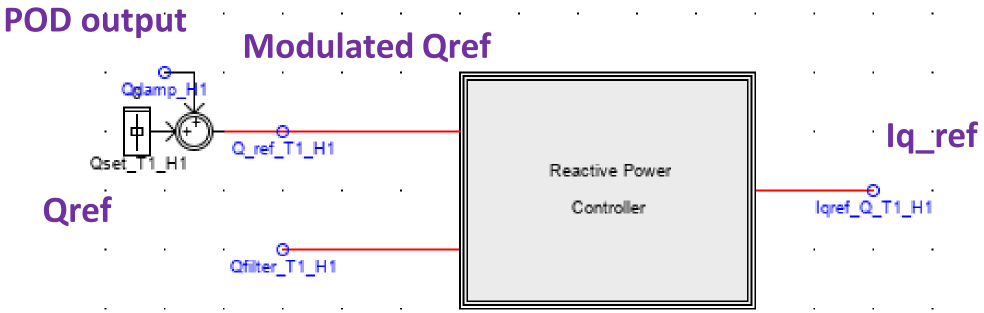
POD Implementation in RTDS

- POD control command was added to Pref, Qref, or both



POD

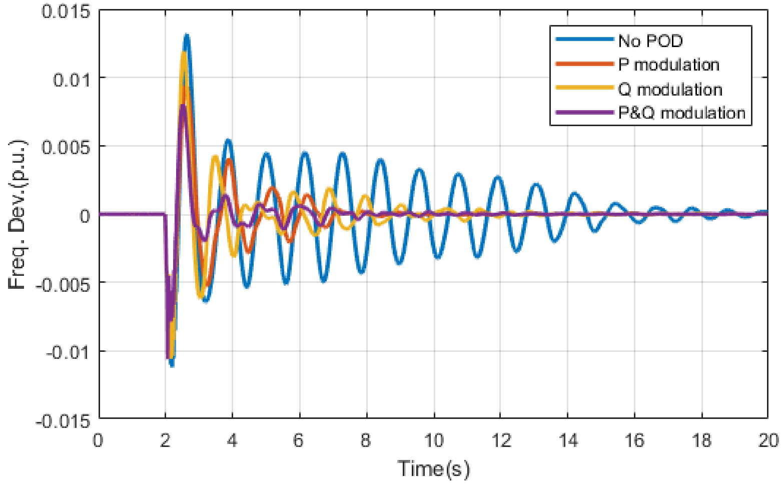


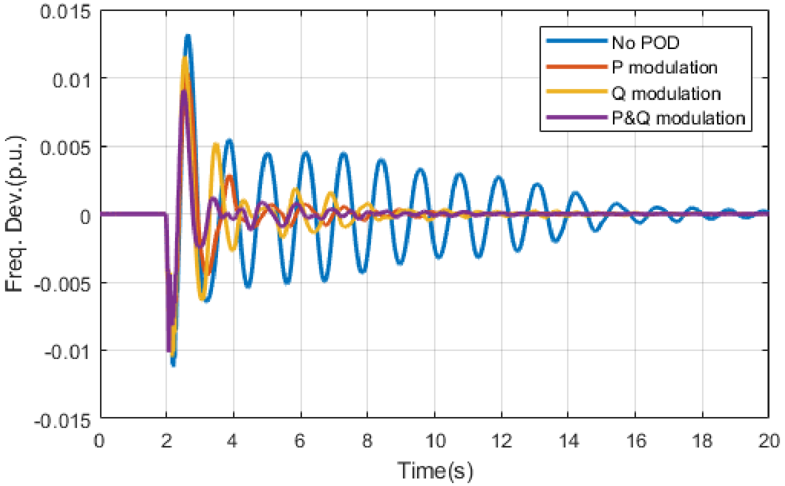


P modulation

Q modulation

POD Control Performance – PowerFactory vs RTDS





Actuator	P or Q modulation	PowerFactory			RTDS		
		Oscillation Freq. (Hz)	Damping Ratio (%)	Relative Damping Ratio Improvement (%)	Oscillation Freq. (Hz)	Damping Ratio (%)	Relative Damping Ratio Improvement (%)
N/A	N/A	0.87	3.3	N/A	0.89	3.1	N/A
E. Coast	P	0.89	7.1	3.8	0.89	8.4	5.3
	Q	0.91	7.0	3.7	0.92	7.7	4.6
	P and Q	0.95	10.1	6.8	0.92	10.8	7.7
E. Coast 2	P	0.93	8.7	5.4	0.86	>15	>11.9
	Q	1.01	7.5	4.2	0.90	12.1	9.0
	P and Q	1.00	>15	>11.7	0.89	>15	>11.9
W. Coast 3	P	0.92	9.1	5.8	0.89	>15	>11.9
	Q	0.91	7.0	3.7	0.89	8.7	5.6
	P and Q	1.01	12.5	9.2	0.87	>15	>11.9
W. Coast 2	P	0.94	8.7	5.4	0.89	12.8	9.7
	Q	0.90	7.2	3.9	0.90	9.9	6.8
	P and Q	1.30	13.1	9.8	0.90	13.1	10.0

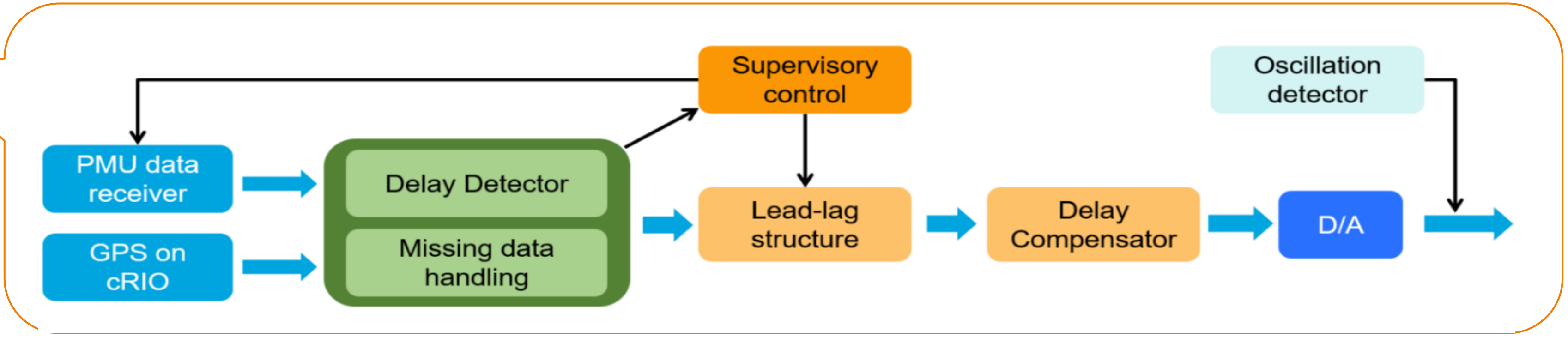
- Consistent Results
- POD performance in RTDS is better compared to PowerFactory

Hardware POD Controller Implementation and Hardware-In-the-Loop Testing

POD Implementation on General Hardware Platform

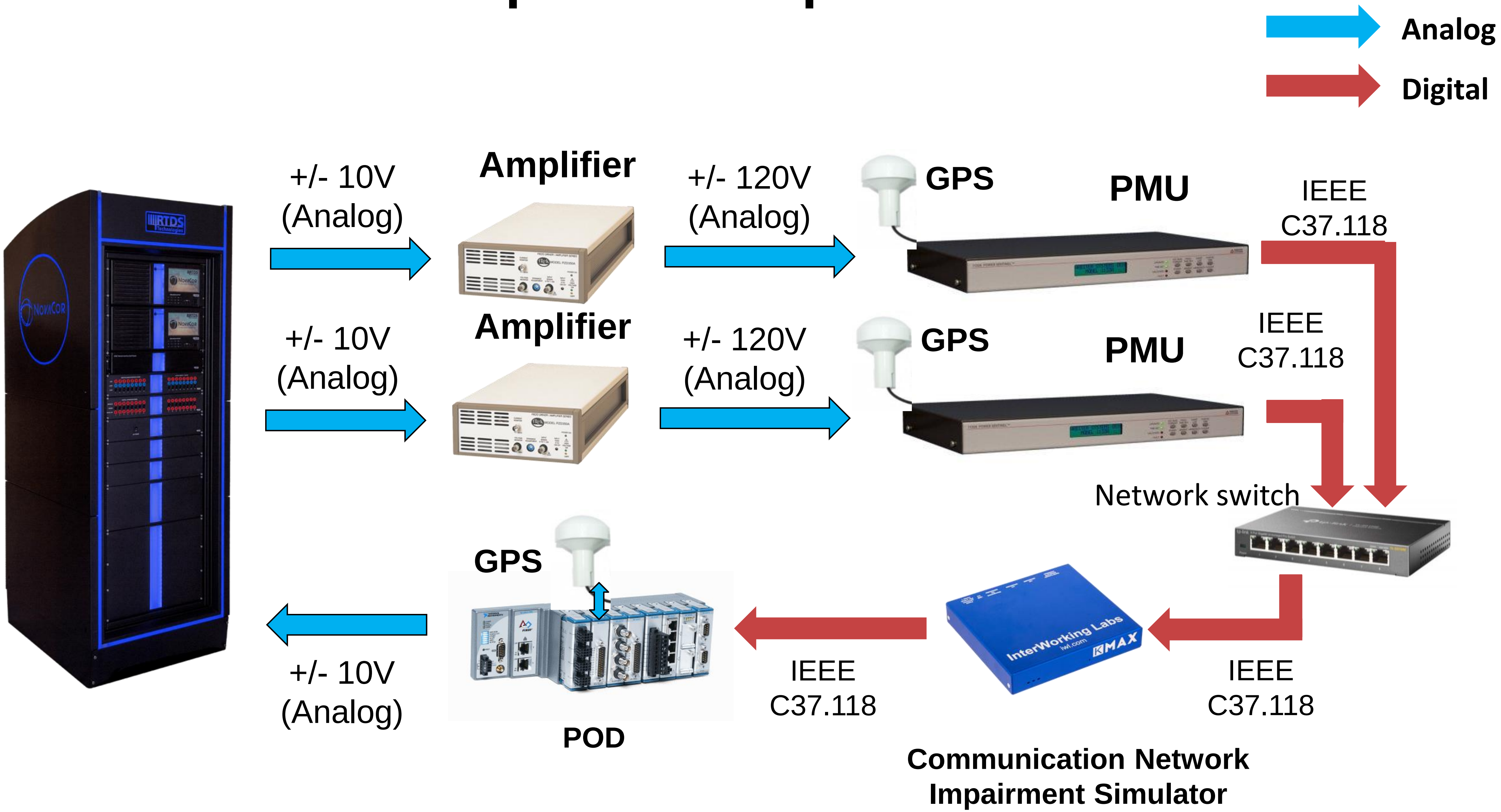
		Block Name	Function
Basic Module	1	PMU data receiver	Unpack PMU data package complying with C37.118
	2	Lead-lag structure	Basic control function
	3	D/A conversion	Convert digital signal to analog signal
Advanced Module	4	GPS module	Capture absolute timestamp
	5	Delay detector	Estimate the time delay
	6	Delay compensator	Eliminate impact of time delay
	7	Missing data handling	Eliminate impact of missing data
	8	Supervisory control	Switch PMU channel, identify transfer function model, determine optimal controller parameters
	9	Oscillation detector	Disable controller if no oscillation

National Instruments CompactRIO



HIL Important to Test POD’s Real Time Operation Under Realistic Operating Conditions

Hardware-In-the-Loop Test Setup



Analog

Digital

+/- 10V (Analog)

Amplifier

+/- 120V (Analog)

GPS

PMU

IEEE C37.118

+/- 10V (Analog)

Amplifier

+/- 120V (Analog)

GPS

PMU

IEEE C37.118

Network switch

GPS

+/- 10V (Analog)

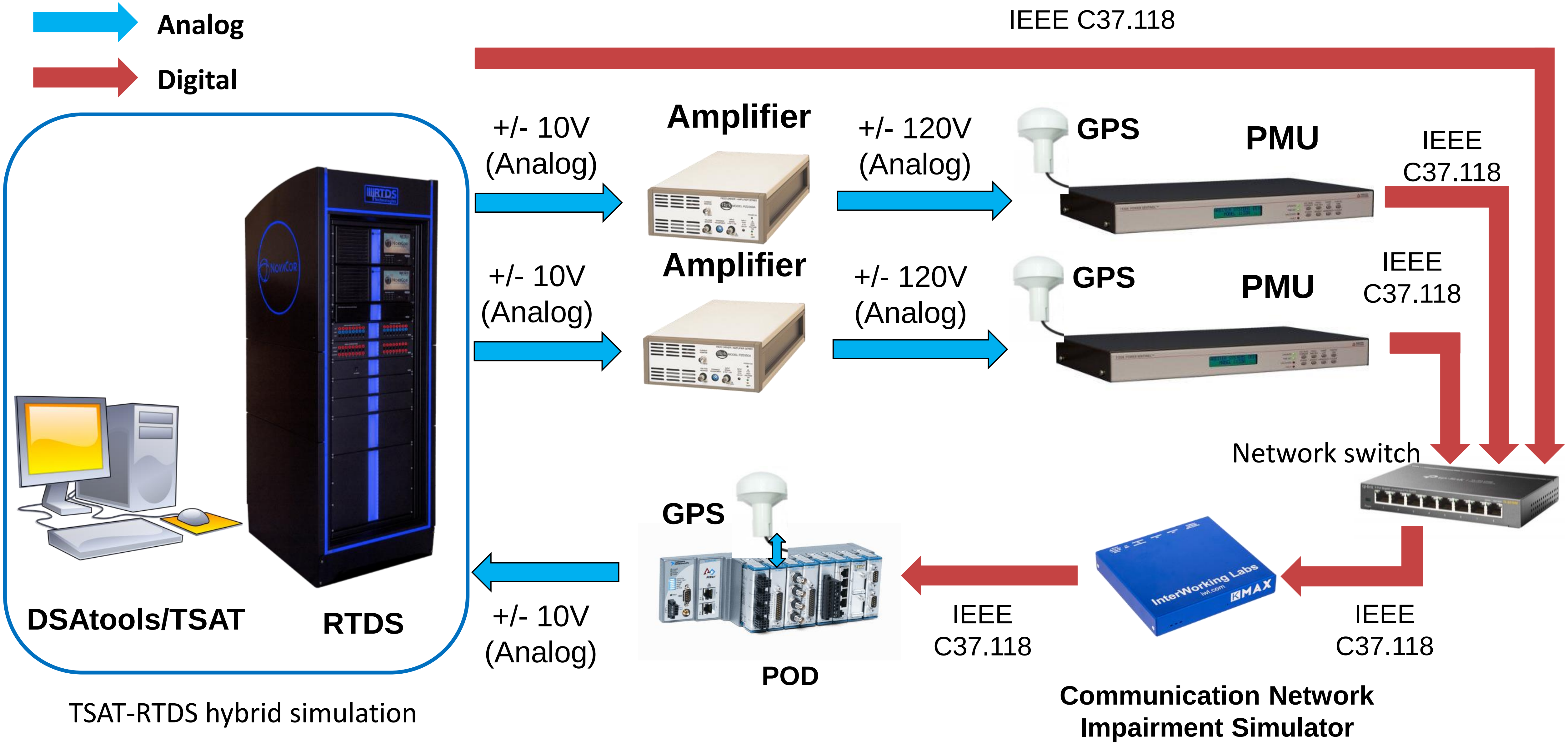
POD

IEEE C37.118

IEEE C37.118

Communication Network Impairment Simulator

RTDS HIL Test Setup at UTK



Analog

Digital

IEEE C37.118

+/- 10V
(Analog)

Amplifier

+/- 120V
(Analog)

GPS

PMU

IEEE
C37.118

+/- 10V
(Analog)

Amplifier

+/- 120V
(Analog)

GPS

PMU

IEEE
C37.118

Network switch

DSAtools/TSAT

RTDS

TSAT-RTDS hybrid simulation

+/- 10V
(Analog)

GPS

POD

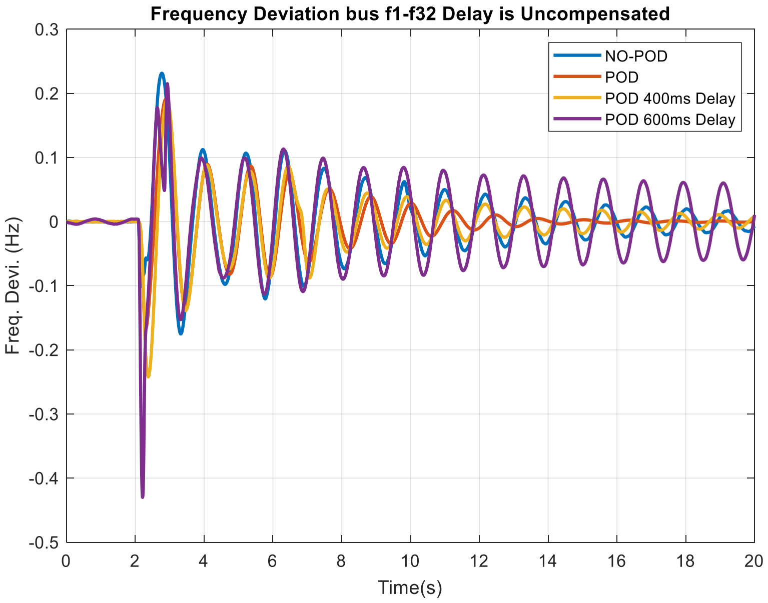
IEEE
C37.118

IEEE
C37.118

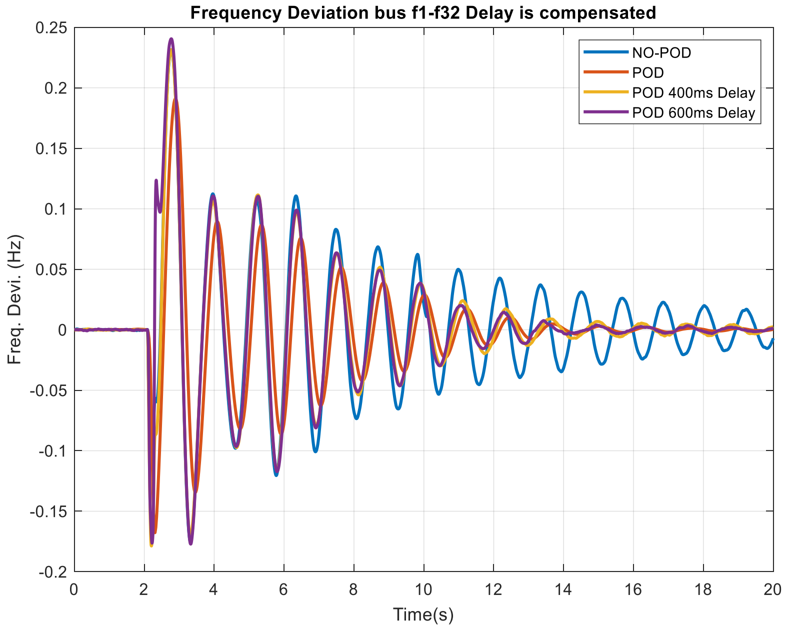
**Communication Network
Impairment Simulator**

POD Performance Under Communication Delays & Data Loss

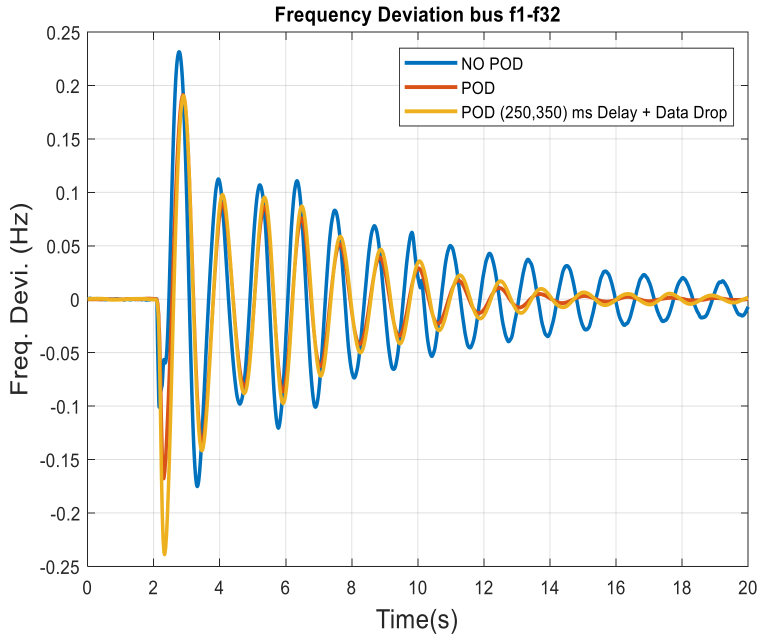
- No delay compensation: POD performance is deteriorated
- With delay compensation: POD can damp the oscillation, and its performance is close to the no delay case
- POD can handle occasional missing data



POD performance under time delay (400 & 600 ms) (No delay compensation)



POD performance under time delay (400 & 600 ms) (With delay compensation)

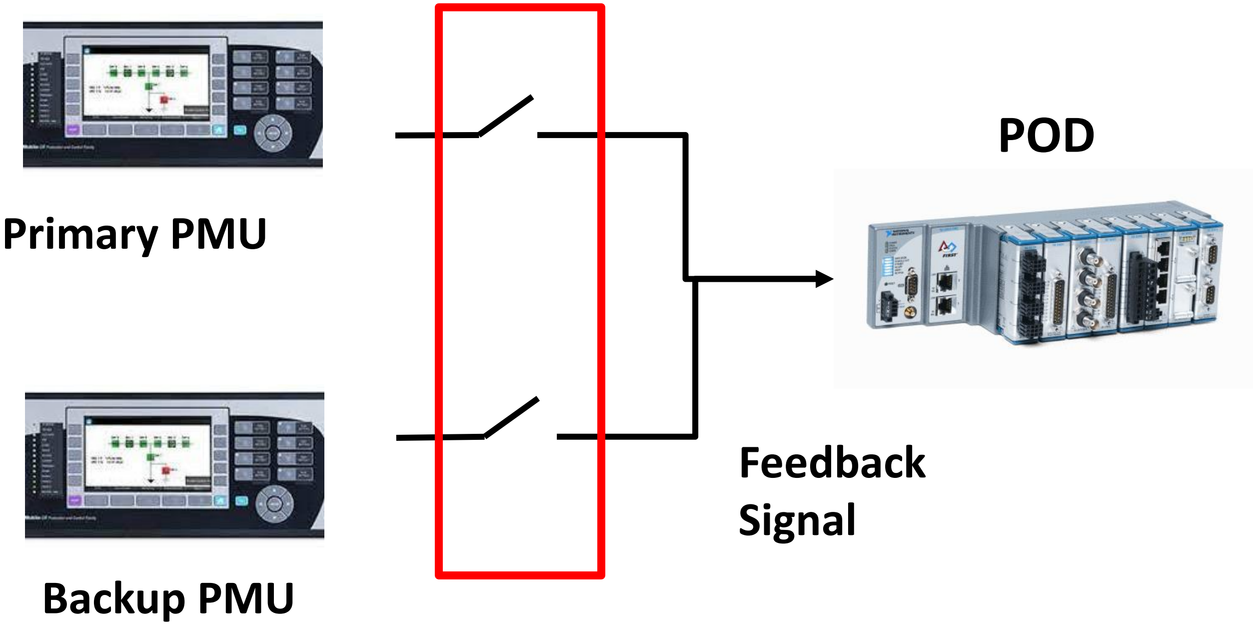


POD performance under random time delay (250-300 ms) and 50% occasional data loss

Consecutive Data Loss with Supervisory Control

Supervisory Control Module

- Switch to backup PMU in case of long delay or loss of primary PMU
- Switch back to primary PMU if its performance is satisfactory



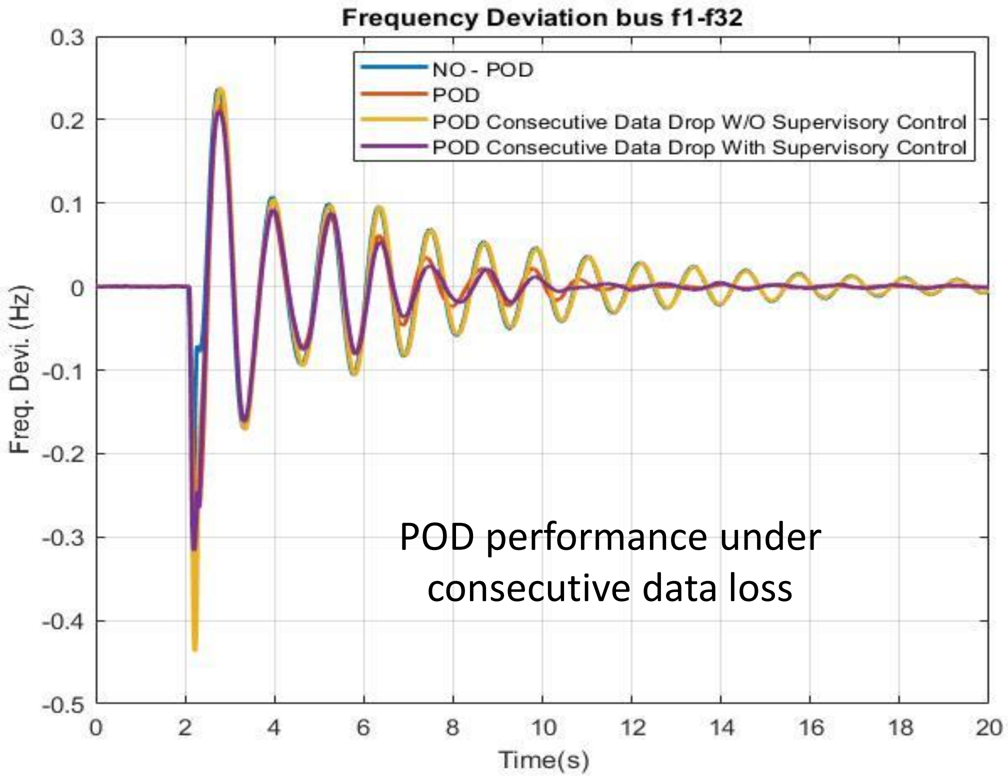
POD

Primary PMU

Backup PMU

Feedback Signal

- Consecutive data loss 1s - 20s
  - With supervisory control, POD can provide sufficient damping control by switching to backup PMU



POD performance under consecutive data loss

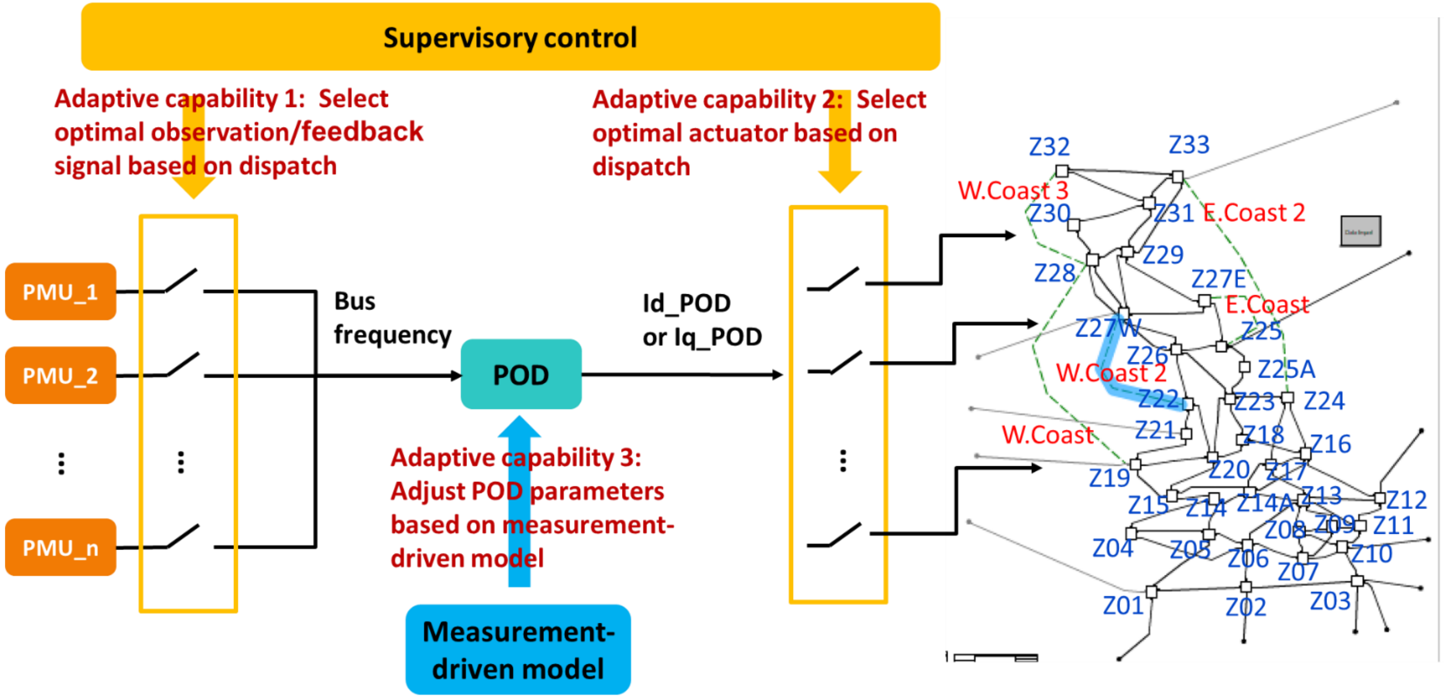
Adaptive POD Performance

Adaptive POD Design

- **For various typical dispatches and for each Mode, developed a look-up table:** Optimal observation/feedback signal, optimal actuator, default POD parameters
- **Adaptive POD 1 to control Mode 1 and POD 2 to control Mode 2:**
  - Select optimal observation signals and actuators based on current dispatch and look-up tables
  - Use default POD parameters based on the look-up table
  - Update POD parameters using transfer function model derived from ambient or ring-down measurements

Offline Stage

Online Stage



Supervisory control

Adaptive capability 1: Select optimal observation/feedback signal based on dispatch

Adaptive capability 2: Select optimal actuator based on dispatch

PMU_1

PMU_2

⋮

PMU_n

Bus frequency

POD

Id_POD or Iq_POD

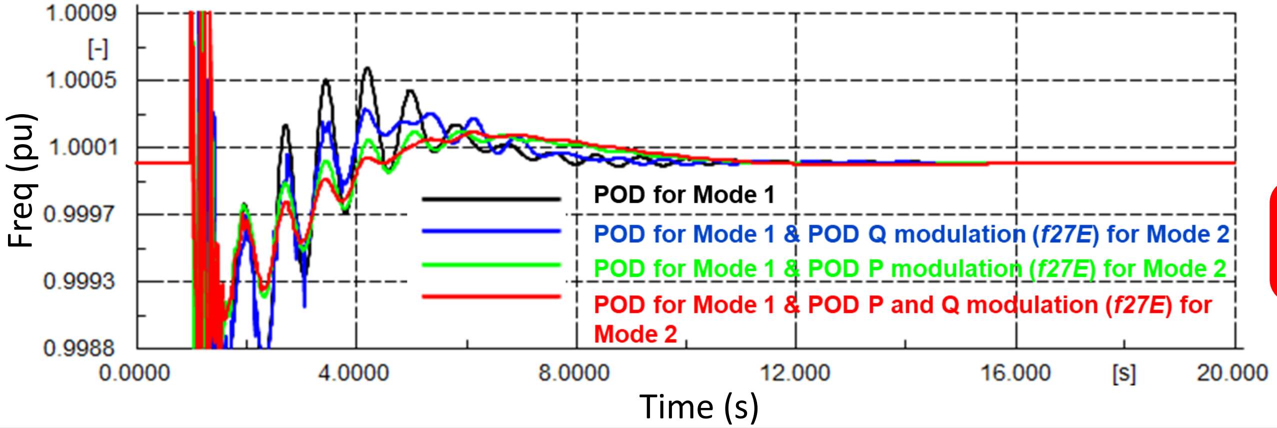
Adaptive capability 3: Adjust POD parameters based on measurement-driven model

Measurement-driven model

Adaptive POD Performance Under Different Dispatches

- Mode 1:
  - Observation signal: Always f1-f32
  - Actuator: W.Coast 3
- Mode 2:
  - Observation signal: f27E or f12-f22
  - Actuator: W. Coast 2
- Adaptive performance demonstrated in both PowerFactory and RTDS

	Dispatch	Mode 1		Mode 2	
		Observation signal	Actuator	Observation signal	Actuator
1	Low load	f1- f32	W.Coast 3 (P&Q)	f27E	W.Coast 2 (P&Q)
2	Intermediate Load	f1- f32	W.Coast 3 (P&Q)	f12-f22	W.Coast 2 (P&Q)
3	High Load	f1- f32	W.Coast 3 (P&Q)	f12-f22	W.Coast 2 (P&Q)

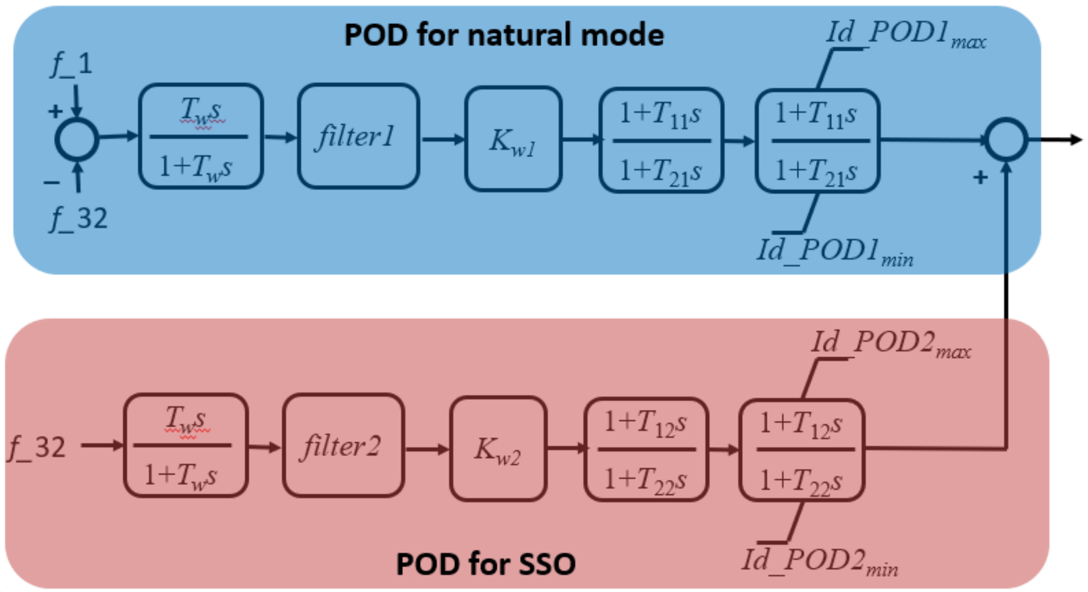


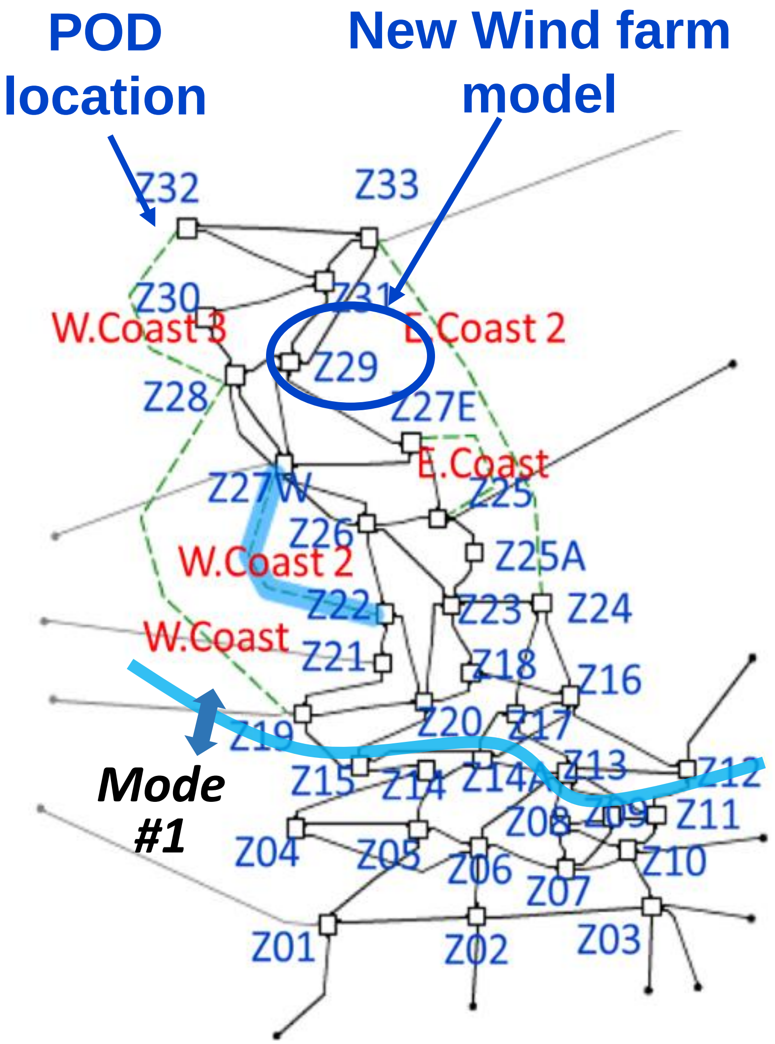
Scenario		Oscillation Freq. (Hz)	Damping Ratio (%)
No POD	N/A	0.85	0.82
P modulation	Non-adaptive	0.83	11.32
	Adaptive	0.83	12.09
Q modulation	Non-adaptive	0.92	4.51
	Adaptive	0.85	>15
P and Q modulation	Non-adaptive	0.87	13.65
	Adaptive	0.85	>15

Sub-Synchronous Oscillation (SSO) Mitigation

POD for Sub-Synchronous Oscillation

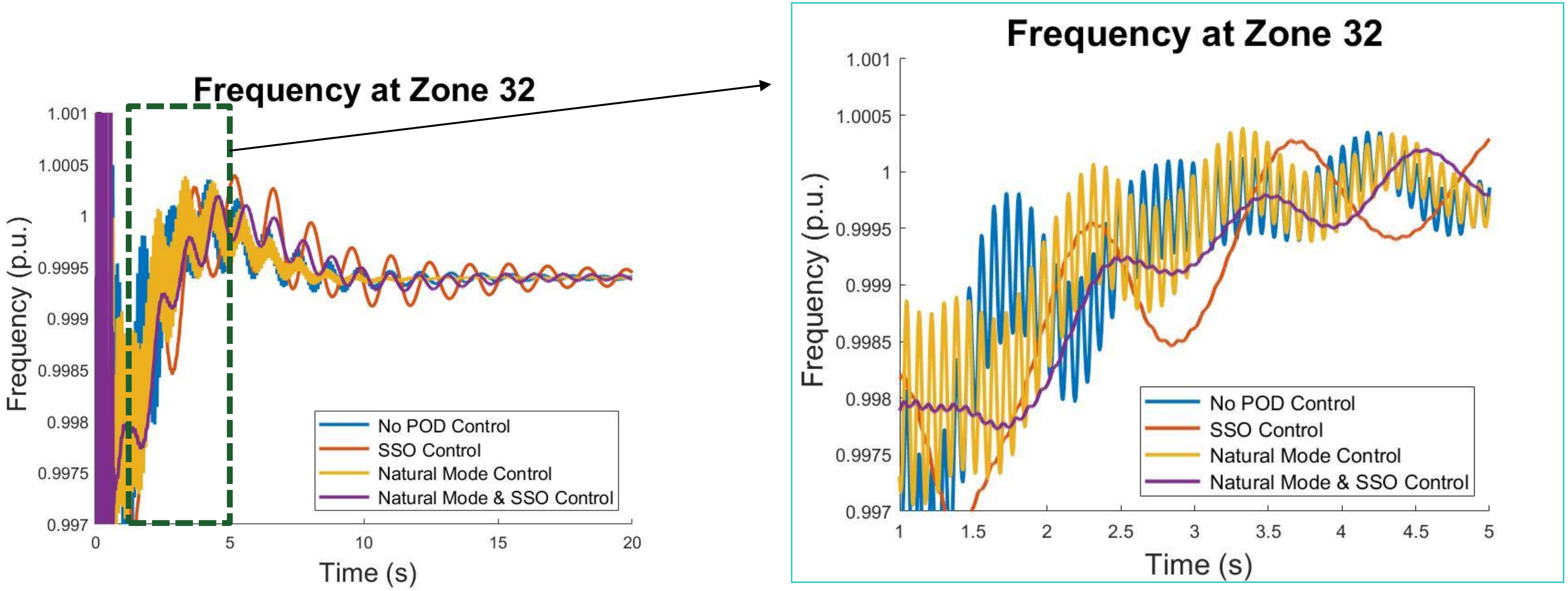
- Replaced original wind model in Zone 29 with a new RMS model that includes representation of PLL and inner current control loops
- The parameters of the inner current control loop controller, outer voltage controller, and PLL were “detuned” to produce SSO
- W.Coast 3 HVDC was used as the actuator to suppress SSO





SSO Simulation Results in PowerFactory

- POD can suppress both natural oscillations and SSO



Summary

HVDC Actuator. P, Q and P&Q Modulation

3 Levels of Adaptive Performance. Validated under Different Grid Dispatches

Coordinated Control of Different System Modes

POD

Measurement Driven Model

Can Suppress SSO

Developed in Hardware and Tested in HIL Setup

Can Handle Communication Delays & Missing Data

Software Implementation in PowerFactory and RTDS

Together…Shaping the Future of Electricity

Adaptive POD applied to HVDC and other large Power Electronic converters

30th September 2021 | Webinar

Benjamin Marshall, Technology Manager
The National HVDC Centre

The National HVDC Centre

Scottish & Southern Electricity Networks
TRANSMISSION

Key Findings- and relevance..

1) **As network becomes more converter dominant, inter-area damping still needed**

Power electronics controllers follow & add to inherent electro-mechanical modes without additional controls. Lower SCL means more modes become apparent, lower and more “lumpy” inertia means more variation of mode shape & frequency across operation

2) **New modes of oscillation occur as the network becomes more converter dominant**

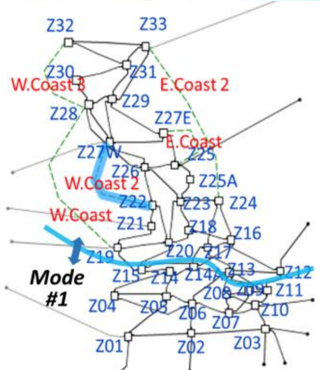
These emerge from the coupling of converters and networks across their operation, typically between 5-15hz, and require damping solutions.

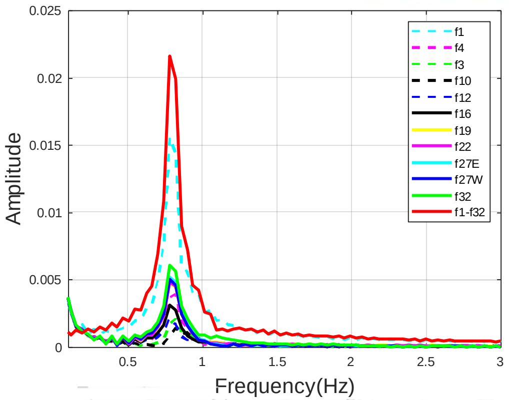
3) **Converters can be used to damp these oscillations providing that an adaptive control strategy is used to instruct that**

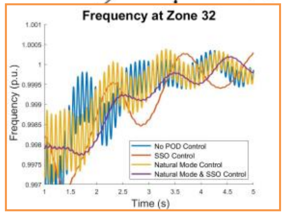
The control structure of POD and related controls will be present in most convertors- and the flexibility to delivered needed damping - it’s the range of tuning that needs careful consideration.

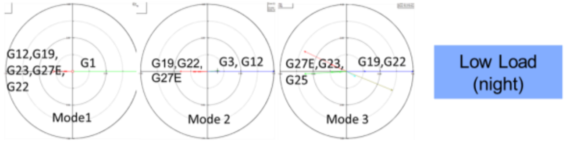
4) **The robustness of POD control strategies can be demonstrated at scale and at complexity in RTDS**

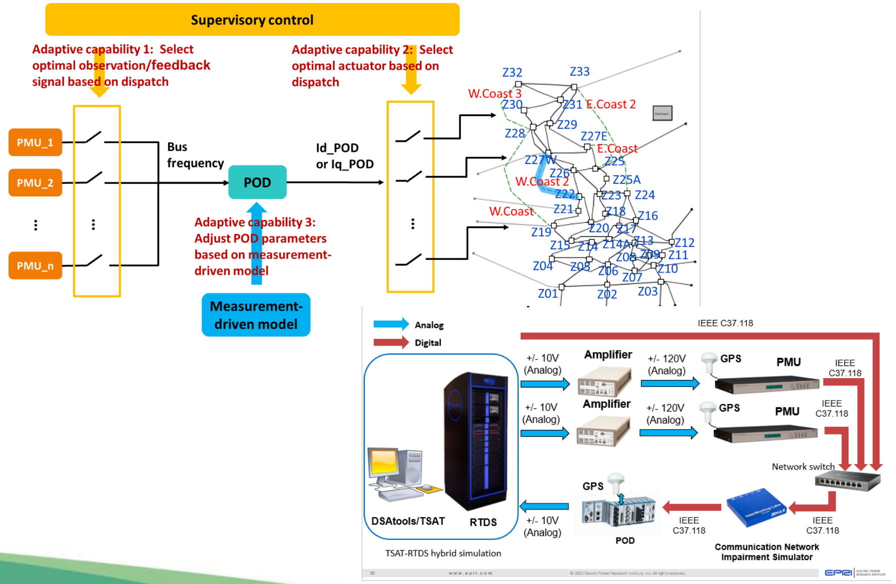
Practical solutions can be delivered.



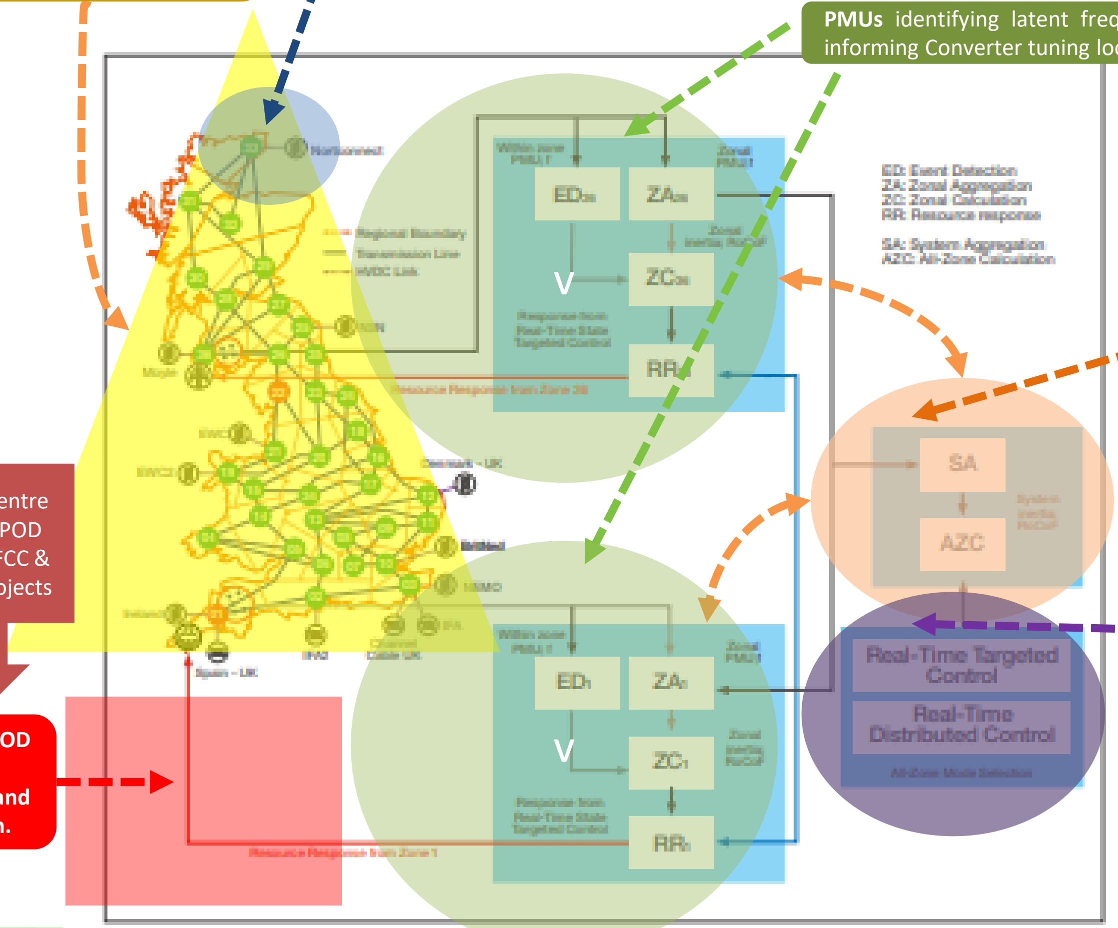








Assembling the picture of a future POD control



HVDC Centre & EPRI POD work

Individual converters with flexible range of damping frequencies, capable of layered damping actions

Operation of the future GB system effectively damped

Visor, EFCC, Phasor control projects, TO programme of PMU delivery

PMUs identifying latent frequencies of oscillation and informing Converter tuning locally

Small signal analysis work, Wide area control simulation, physical C&P and "PSCAD in the loop" of RTDS

Supervisory approaches- Small signal analysis techniques identifying new states of risk+ classical frequencies of concern- to then inform local detection and control

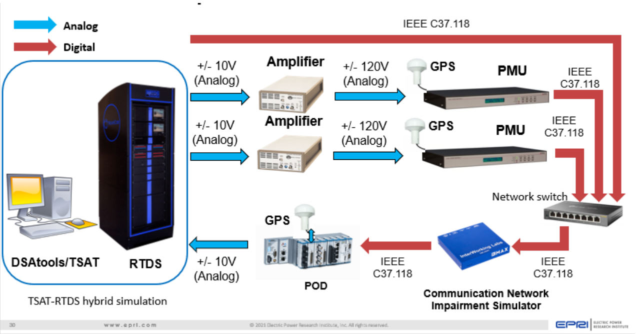
HVDC Centre & EPRI POD work

Optimisation approaches- optimal allocation of converters and other resources to damp oscillations identified

HVDC Centre & EPRI POD work, EFCC & Visor projects

Robust POD control design, and operation.

(image from EFCC project https://www.nationalgrideso.com/document/144441/download)

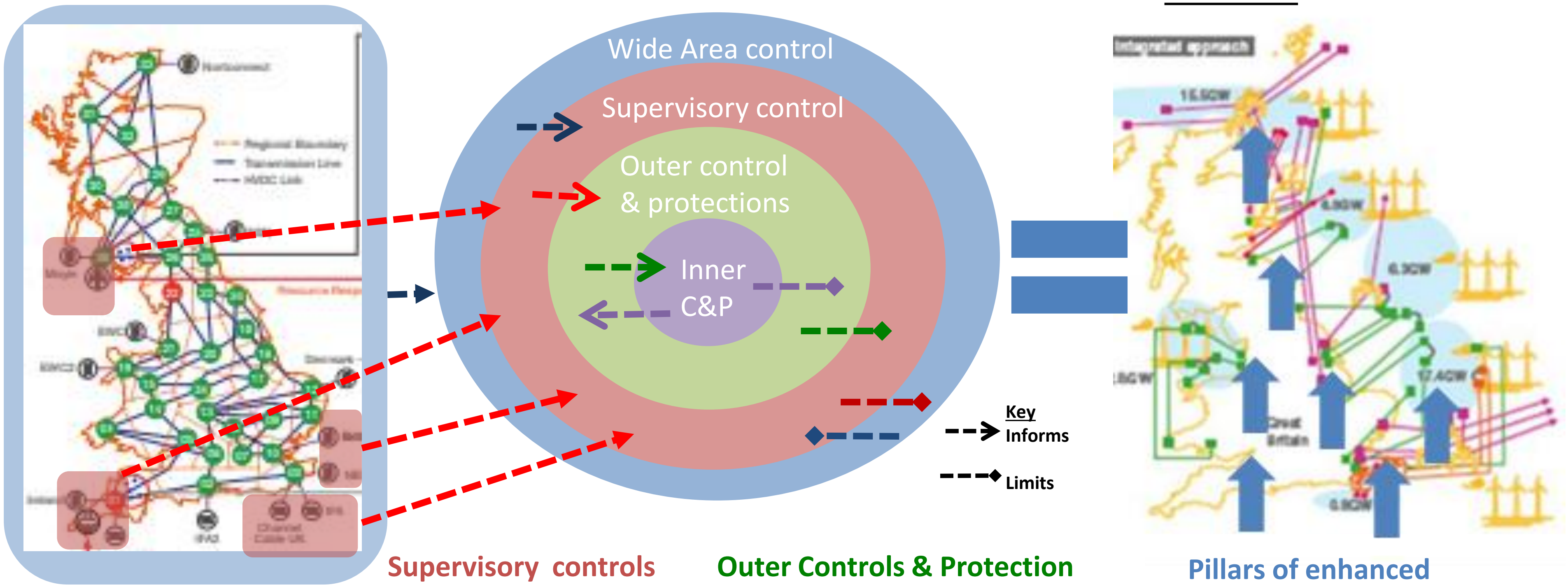


Beyond POD..
A family of controls for a stable network

Systems

Layers of Co-ordinated control by device

Outcome



Wide Area controls-
Frequency management, Oscillation damping, classical and non-classical voltage & angle stability, Thermal management. Protective relay actions?

Supervisory controls
Local interaction & control hunting management, management/ rationing of behaviours under limits; e.g. grid forming limits; current limits & multiple disturbance cases

Outer Controls & Protection
+ Inner control loop C&P
Delivering AC network performance, respecting device and DC circuit needs, informed by Wide Area and Supervisory control needs together providing technical code compliant device behaviour, via proprietor IP solutions

Pillars of enhanced regional stability across GB system
Via co-ordinated and compatible device and network oriented controls and protections.

Thanks for listening.

Any questions, please?

- ☐ For further information, please visit www.hvdccentre.com ; OR email: info@hvdccentre.com

The National HVDC Centre

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Q&A Session

❑ **Speakers:**

- Evangelos Farantatos -Electric Power Research Institute (EPRI)
- Benjamin Marshall – The National HVDC Centre

❑ **Moderator:**

- Md Habibur Rahman – The National HVDC Centre