

Controller-Hardware-in-the-Loop Validation of Coordinated Dynamic Reactive Power Control in Offshore Wind Farms Using a Fast-Switching Variable Shunt Reactor

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Agenda

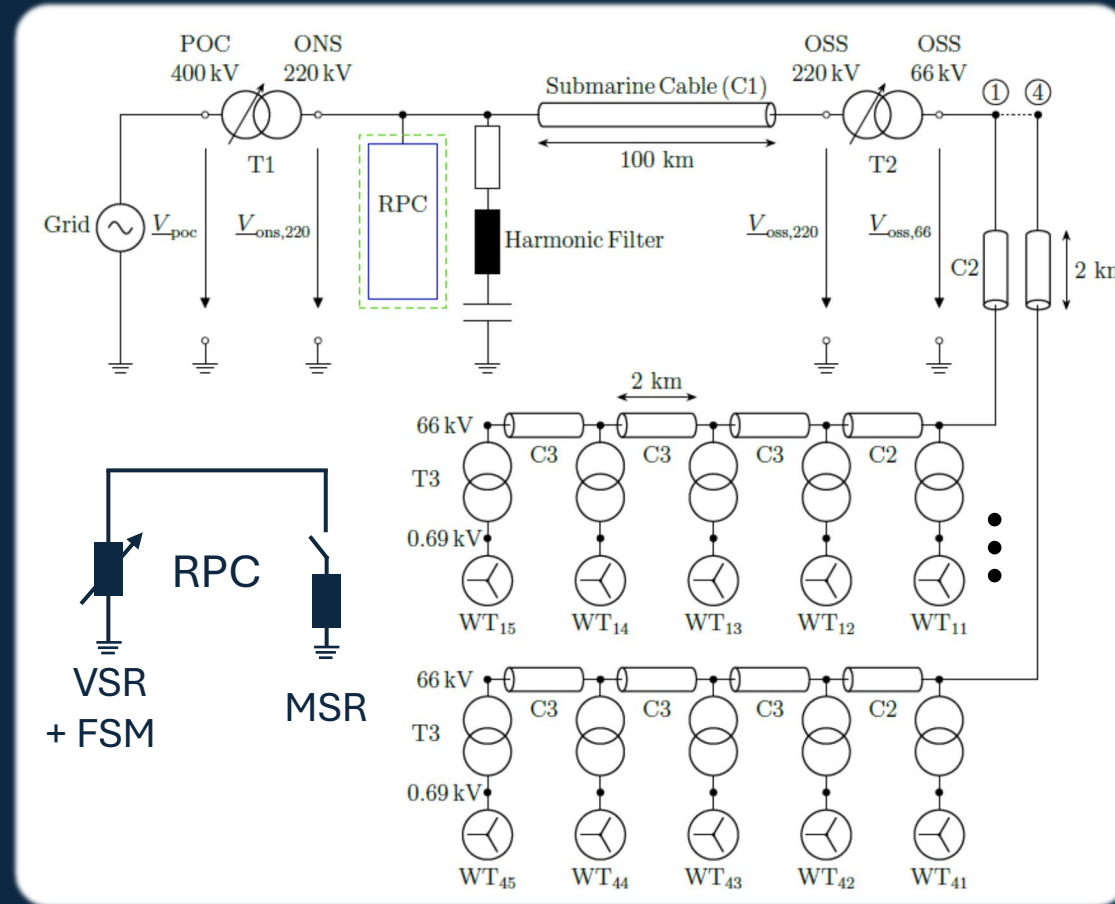
1. AC Connected Offshore Wind Farm
2. Fast-Switching Variable Shunt Reactor
3. Grid Code Requirements
4. Coordinated Control Scheme
5. Controller-Hardware-in-the-Loop Setup
6. Conclusion and Outlook

AC Connected Offshore Wind Farm

Grid Topology and Key Parameters

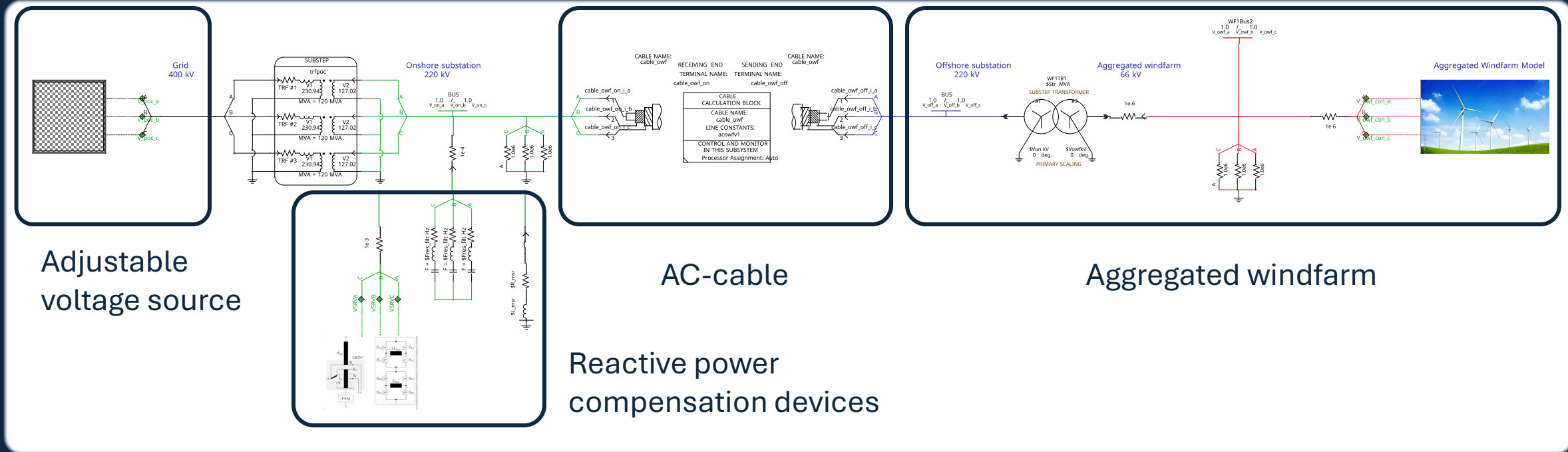
Offshore Wind Farm

- **20** wind turbines in total
- **360 MW** nominal active power
- **4** turbine arrays connected to the offshore substation
- **360 MVA** transformer (T2: 220 kV / 66 kV)



- **100 km** AC-Cable connects the wind farm to the onshore substation
- Reactive power compensation devices at the onshore substation
- **360 MVA** transformer connection to the transmission grid (T1: 400 kV / 220 kV)

Modelling in RSCAD



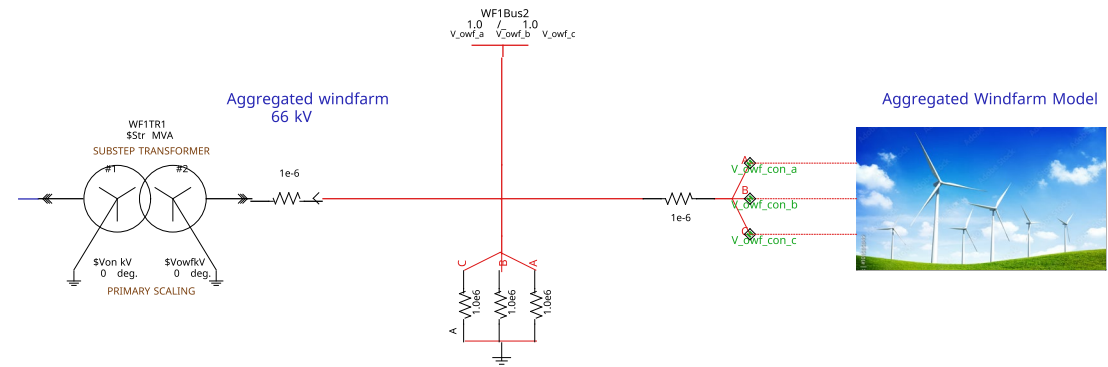
Modelling in RSCAD – Wind Farm

Example case as aggregated wind farm model

Transformer scaling factor is adjusted to achieve a total nominal active power of 360 MW

Gain and integrator time constant of the turbine reactive power control constant are adjusted

Reactive power setpoint is part of the coordinated control scheme



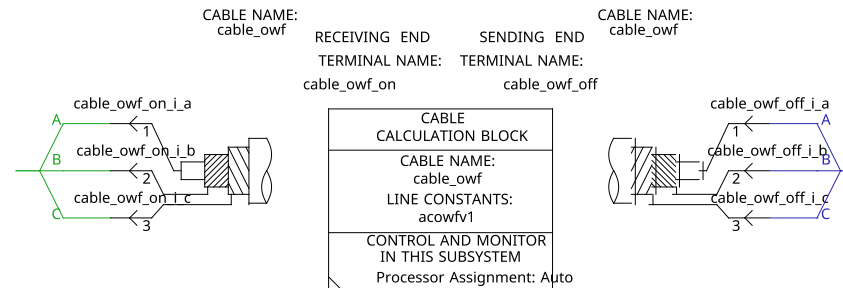
RSCAD wind farm example case
(PMSM_Farm_LrgDT_AVM)

Modelling in RSCAD – AC-Cable

Modelled as Bergeron model
as the focus is on reactive
power compensation

Modelled using
the cable module

Sending end on the
offshore substation



100 km AC-cable as
Bergeron model.

Parameter	Value
$R'_{(1)}$	$0.039 \frac{\Omega}{\text{km}}$
$X'_{(1)}$	$0.12 \frac{\Omega}{\text{km}}$
$X'_{C,(1)}$	$16.75 \frac{\text{k}\Omega}{\text{km}}$
$R'_{(0)}$	$0.15 \frac{\Omega}{\text{km}}$
$X'_{(0)}$	$0.12 \frac{\Omega}{\text{km}}$
$X'_{C,(0)}$	$16.75 \frac{\text{k}\Omega}{\text{km}}$

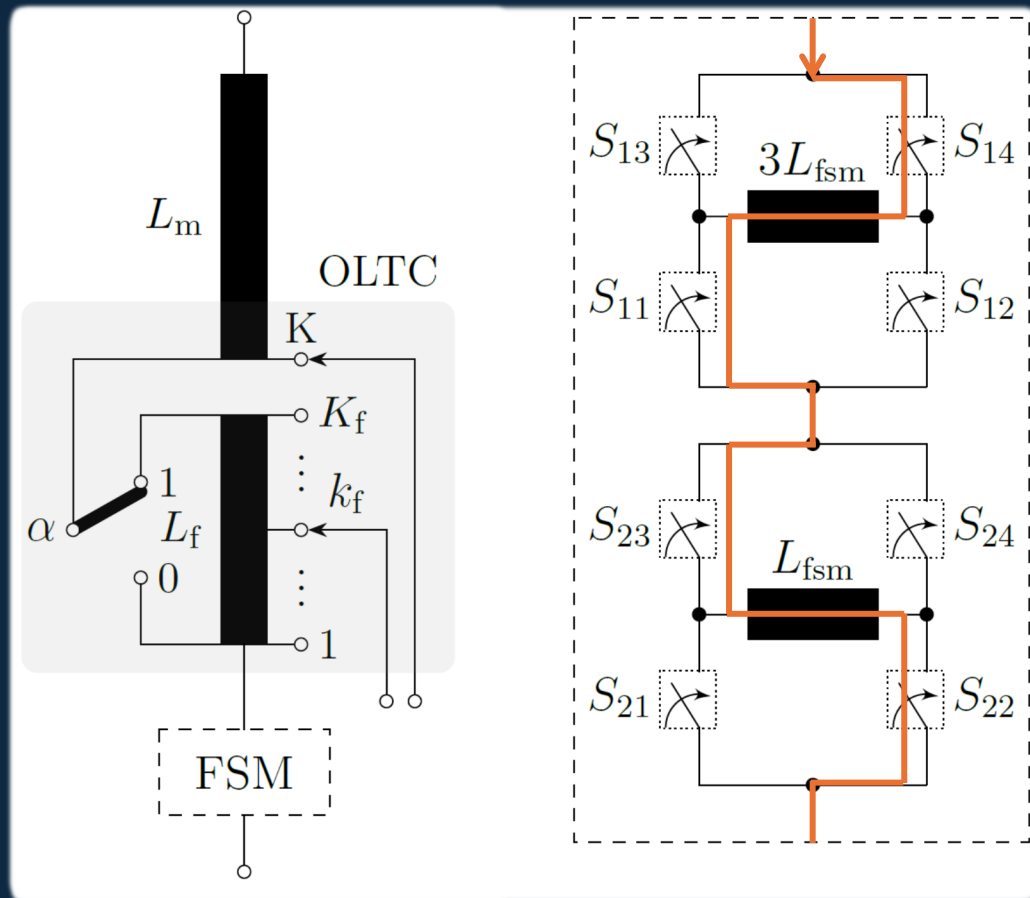
RLC-filter with capacitive reactive power

Parameter	Value
Q_{msr}	95 MVar
$\frac{P_v}{Q}$	0.2 %
Q_{RLC}	50 MVar
f_{res}	300 Hz

Fast-Switching Variable Shunt Reactor

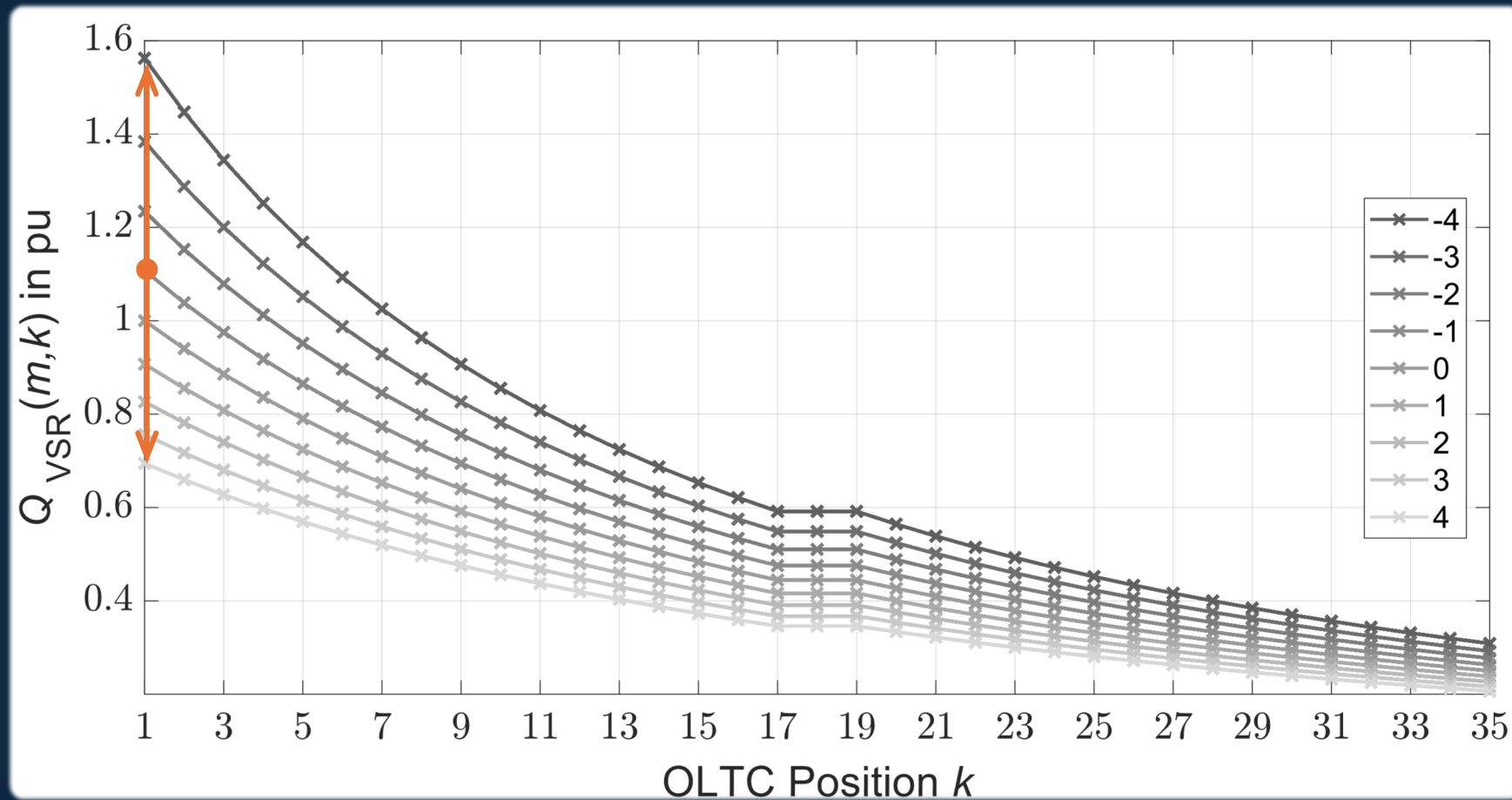
Topology and System Modelling

Enhancing the Conventional VSR



m	S_{11}	S_{12}	S_{13}	S_{14}	S_{21}	S_{22}	S_{23}	S_{24}
-4	1	0	0	1	1	0	0	1
-3	1	0	0	1	0	1	0	1
-2	1	0	0	1	0	1	1	0
-1	1	0	1	0	1	0	0	1
0	0	1	0	1	1	0	1	0
1	0	1	0	1	0	1	1	0
2	0	1	1	0	1	0	0	1
3	0	1	1	0	1	0	1	0
4	0	1	1	0	0	1	1	0

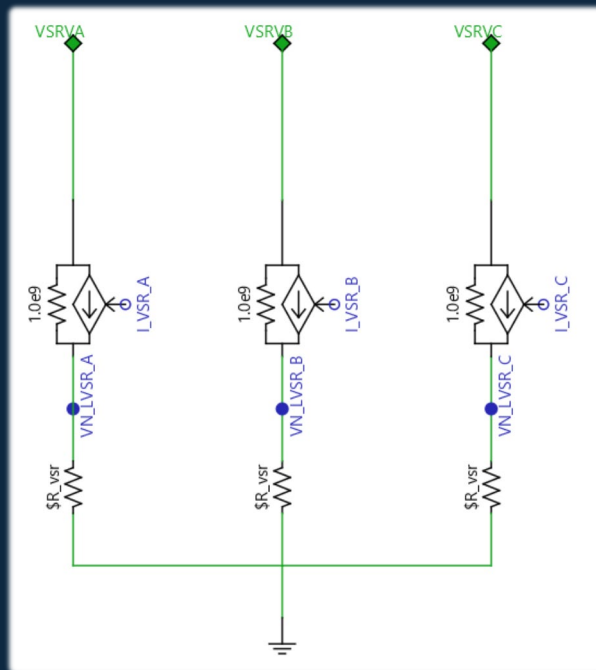
Reactive Power and Switching Positions



- Less than 20 ms switching time
- Ability to skip positions

→ **Highly dynamic reactive power adjustment**

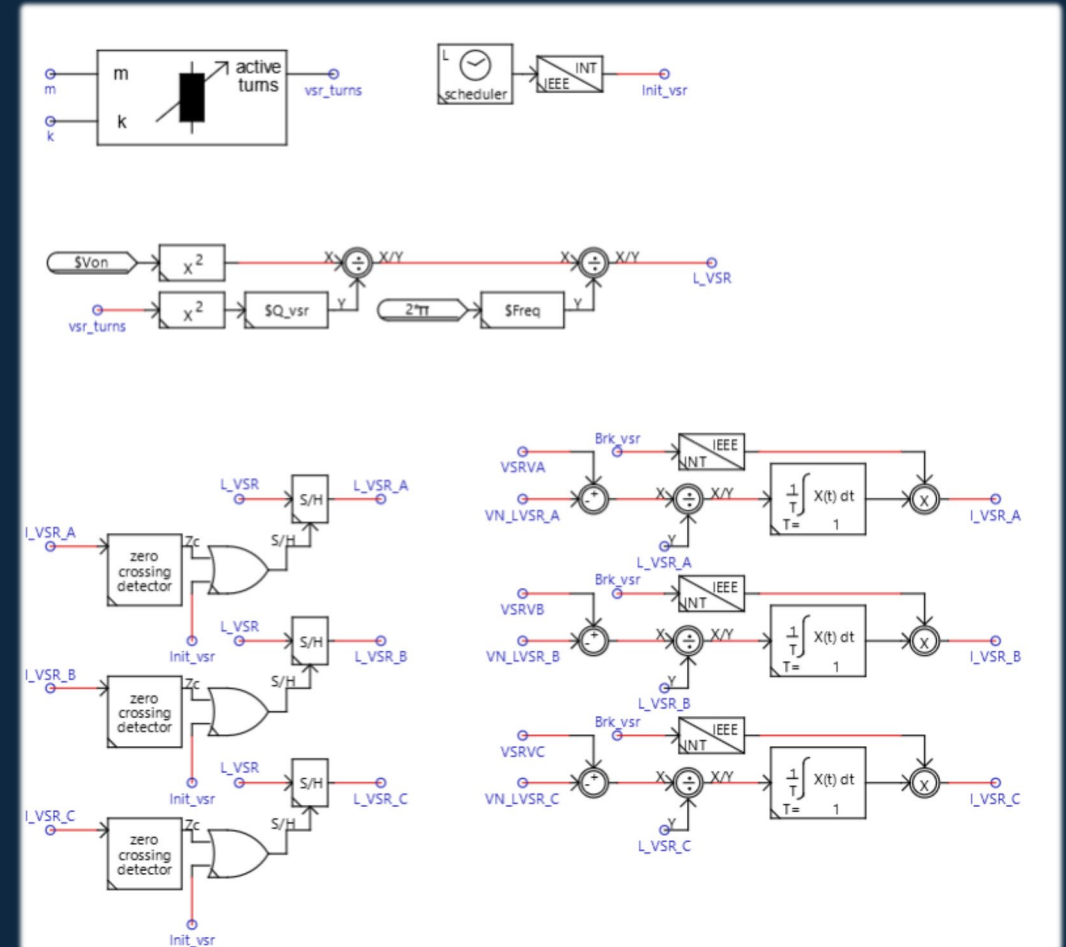
Modelling in RSCAD



Enhanced VSR
modelled as
controlled current
source

Fast-Switching
Module uses zero
current switching

Inductance is
scaled according to
the tap position

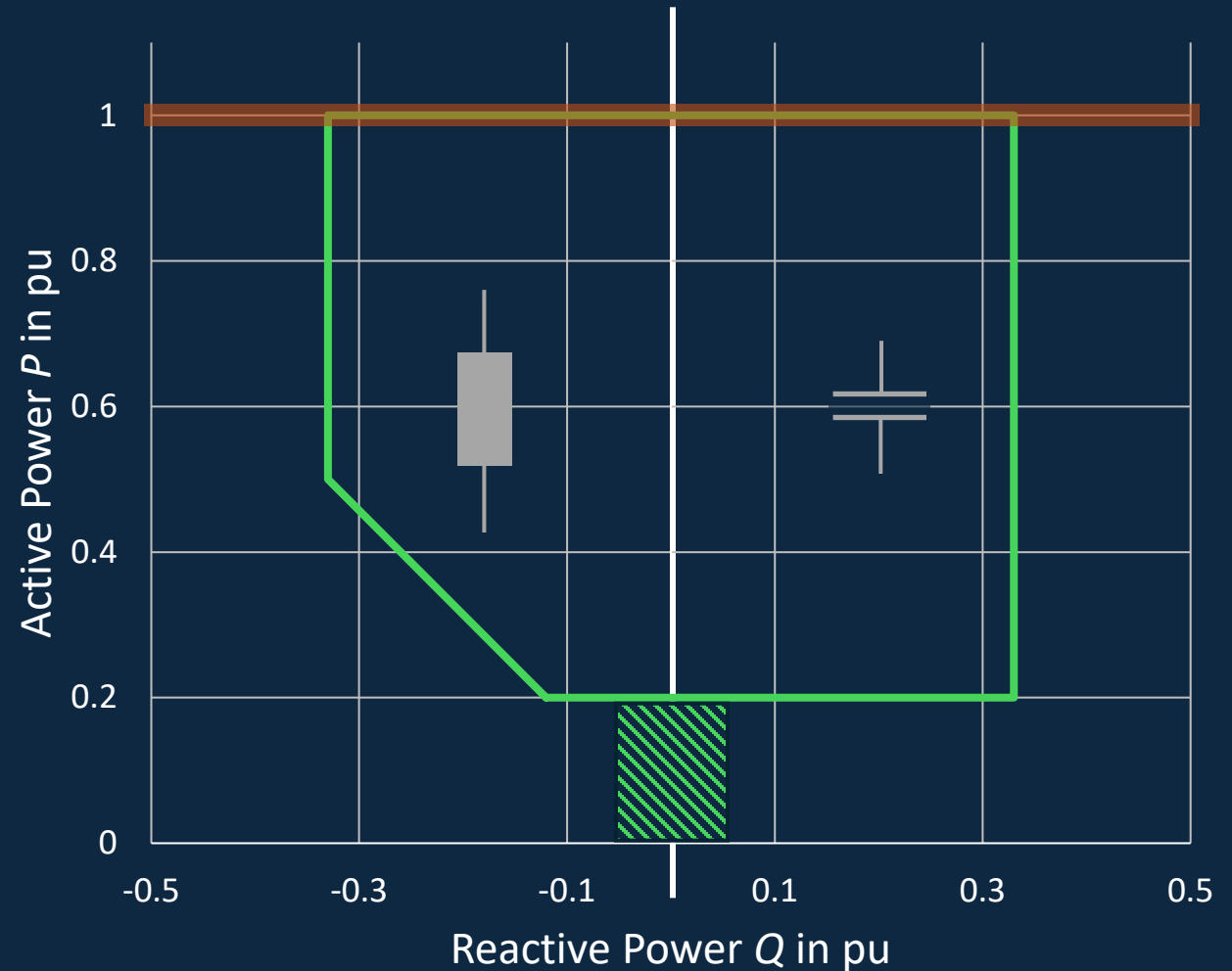


Grid Code Requirements

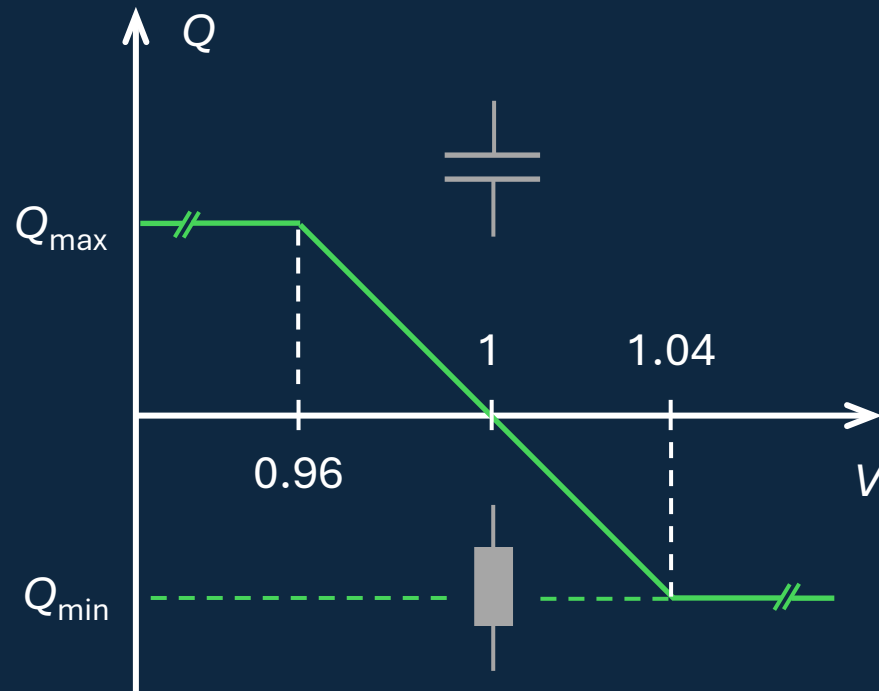
Reactive Power Capability According to NESO Grid Code

Reactive Power Capability according to the UK Grid Code

- At nominal active power, reactive power of up to **0.33 pu** leading and lagging must be deployable
- Capacitive reactive power of **0.33 pu** must be deployable throughout the active power range of 0.2 pu and 1 pu
- Inductive reactive power is descending from **-0.12 pu** at 0.2 pu active power to **-0.33 pu** at 0.5 pu active power
- For simulative investigation an active power infeed of **1 pu** is considered, resulting in the most challenging reactive power requirements



Voltage Droop and Requirements on Dynamic Response



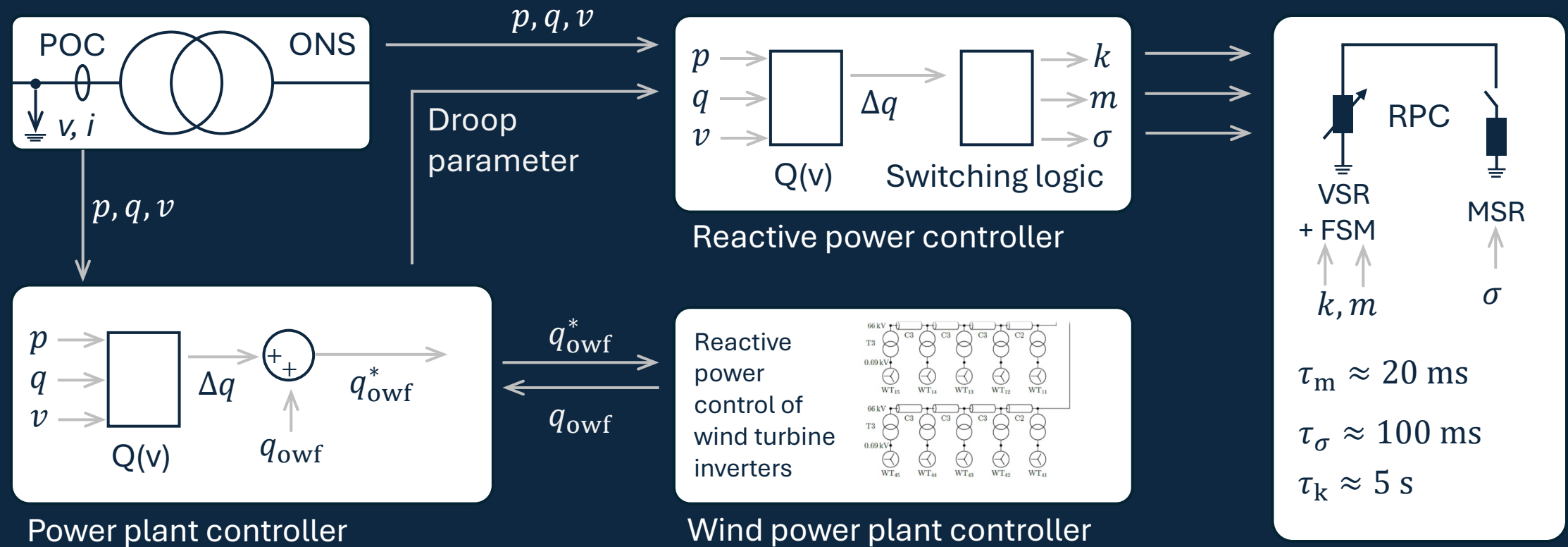
- 4 % slope resulting in $Q_{\min}$ at 1.04 pu and $Q_{\max}$ at 0.96 pu
- Dead time: **0.2 s**
- 90 % Rise time:
 - **1 s** ($0 \rightarrow Q_{\max}/Q_{\min}$)
 - **2 s** ($Q_{\min} \leftrightarrow Q_{\max}$)
- 5 % settling time: **5 s** after 90 % threshold

Coordinated Control Scheme

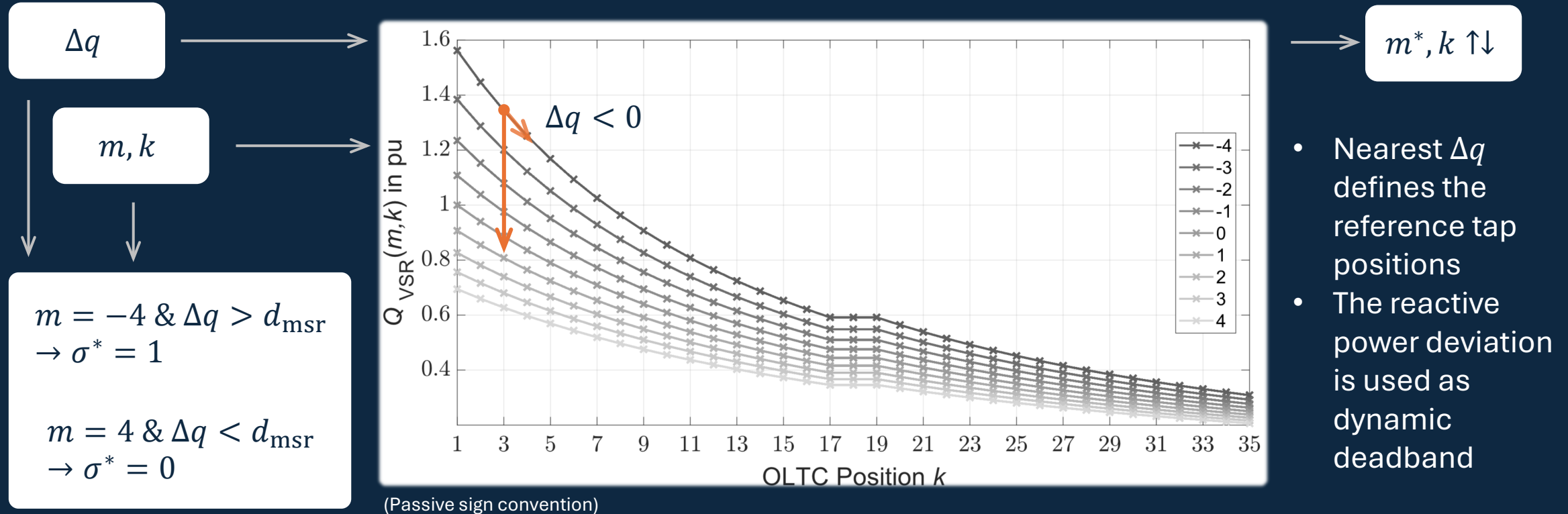
Coordination Between Fast-Switching VSR, Offshore Wind Farm and Mechanically Switched Reactor

Control Structure

Measurement and calculation



Switching Logic



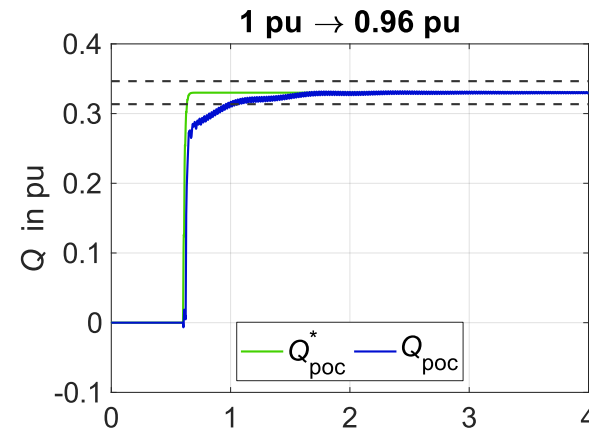
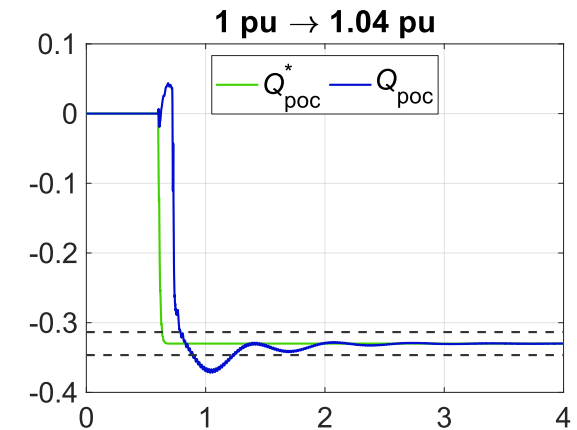
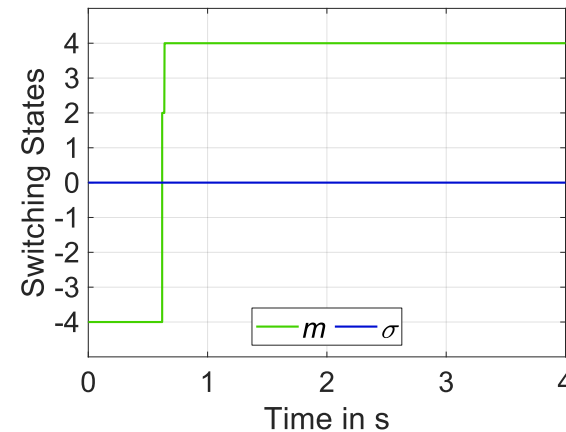
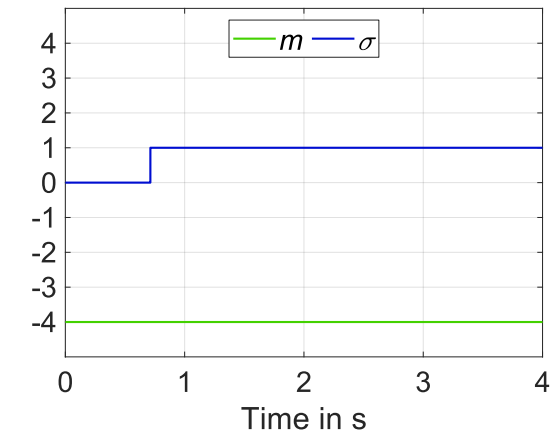
Response on Voltage Step 1 → 0.96 / 1.04

1 → 0.96:

- FSM switches from -4 to 4
- 5 % settling band reached in less than 400 ms

1 → 1.04:

- MSR is switched on, approx. 120 ms
- 5 % settling band reached in less than 700 ms



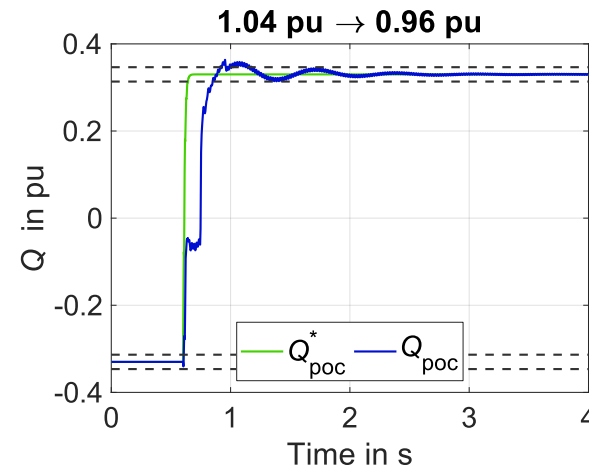
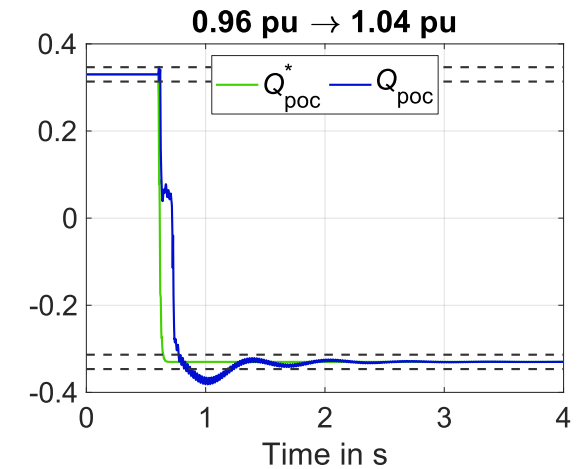
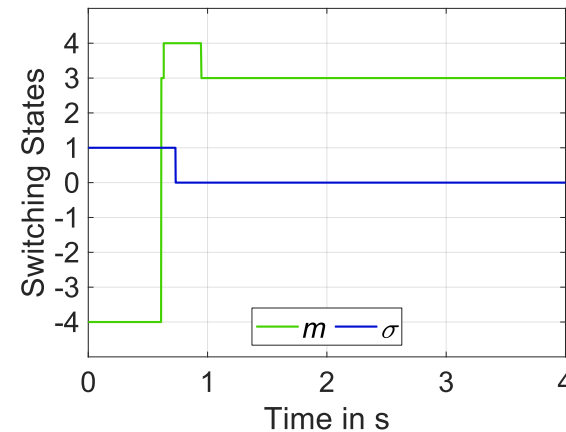
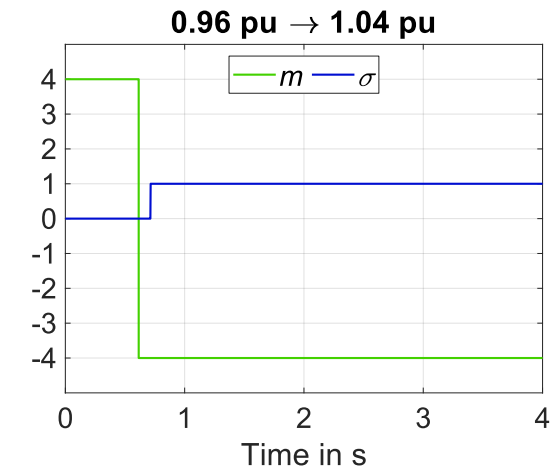
Response on Voltage Step 0.96 ↔ 1.04

1.04 → 0.96:

- FSM switches from -4 to 4
- MSR is switched off after approx. 140 ms
- 5 % settling band reached in less than 800 ms

0.96 → 1.04:

- FSM switches from 4 to -4
- MSR is switched on after approx. 130 ms
- 5 % settling band reached in less than 700 ms

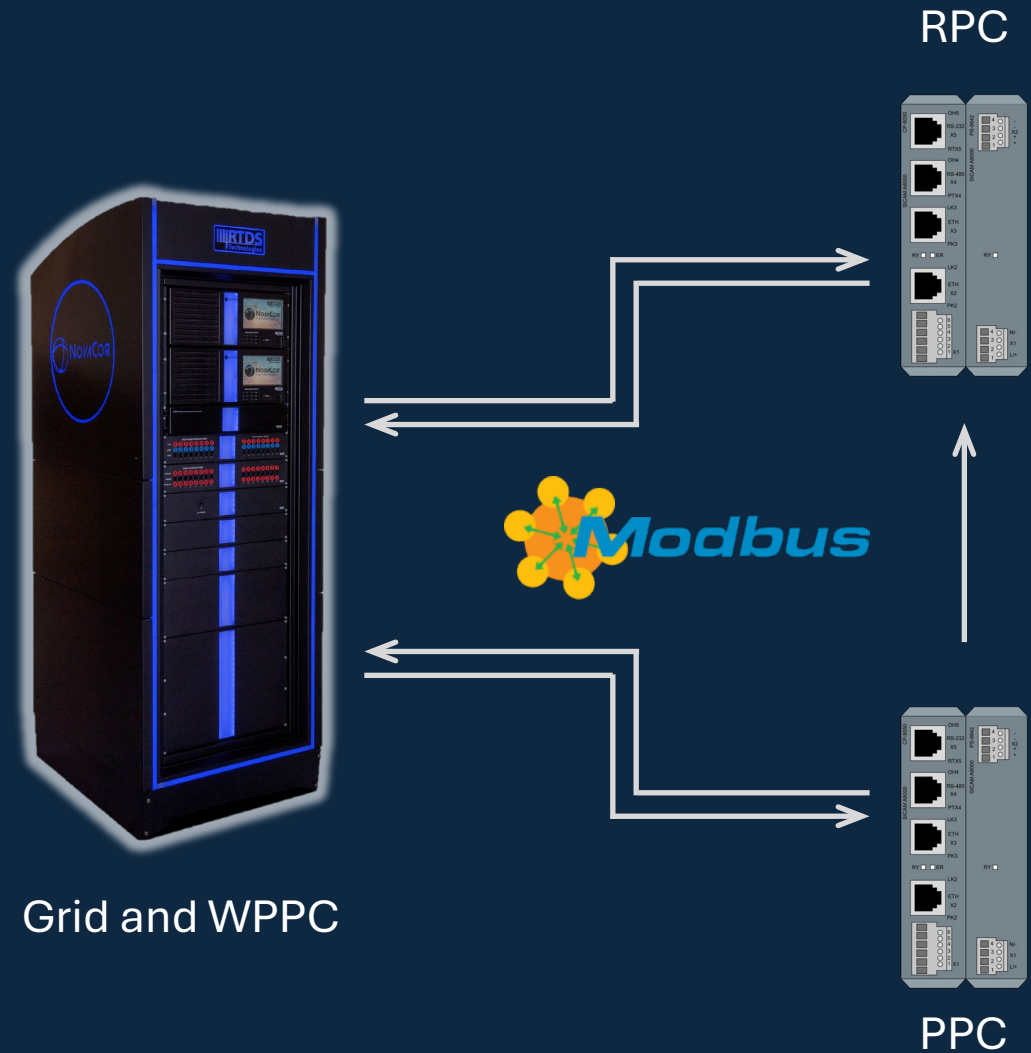


Controller-Hardware-in-the-Loop Setup

Implementation on Industrial Controllers and Simulation Results

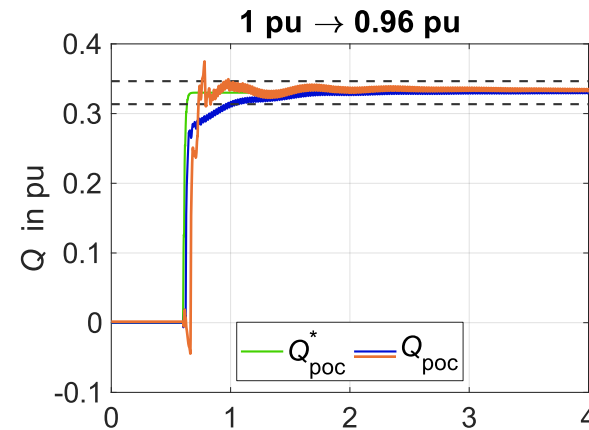
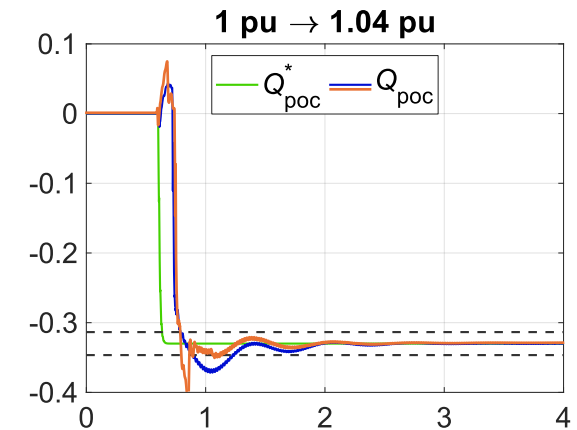
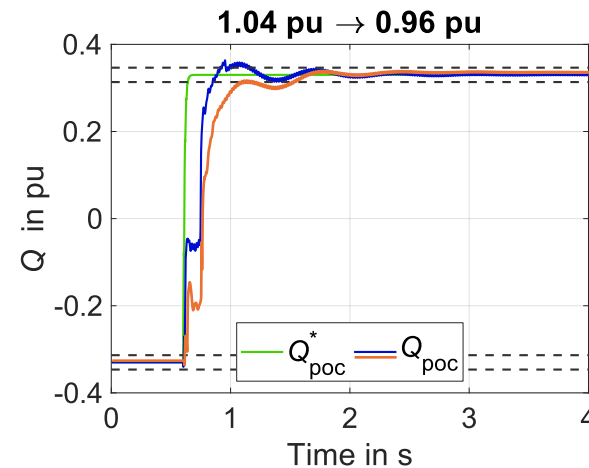
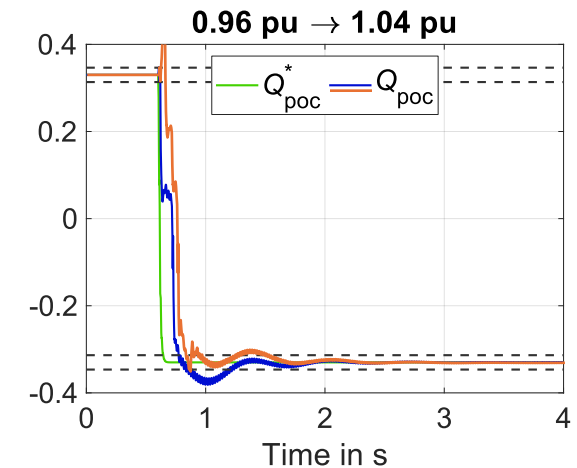
Laboratory Setup

- Siemens SICAM A8000 as industrial controller
- RPC and PPC on separated controllers
- Control functions implemented as containerized applications (SIAPPs)
- Modbus TCP as communication protocol
- PPC as Modbus client and server for communication with RPC
- RPC as Modbus client



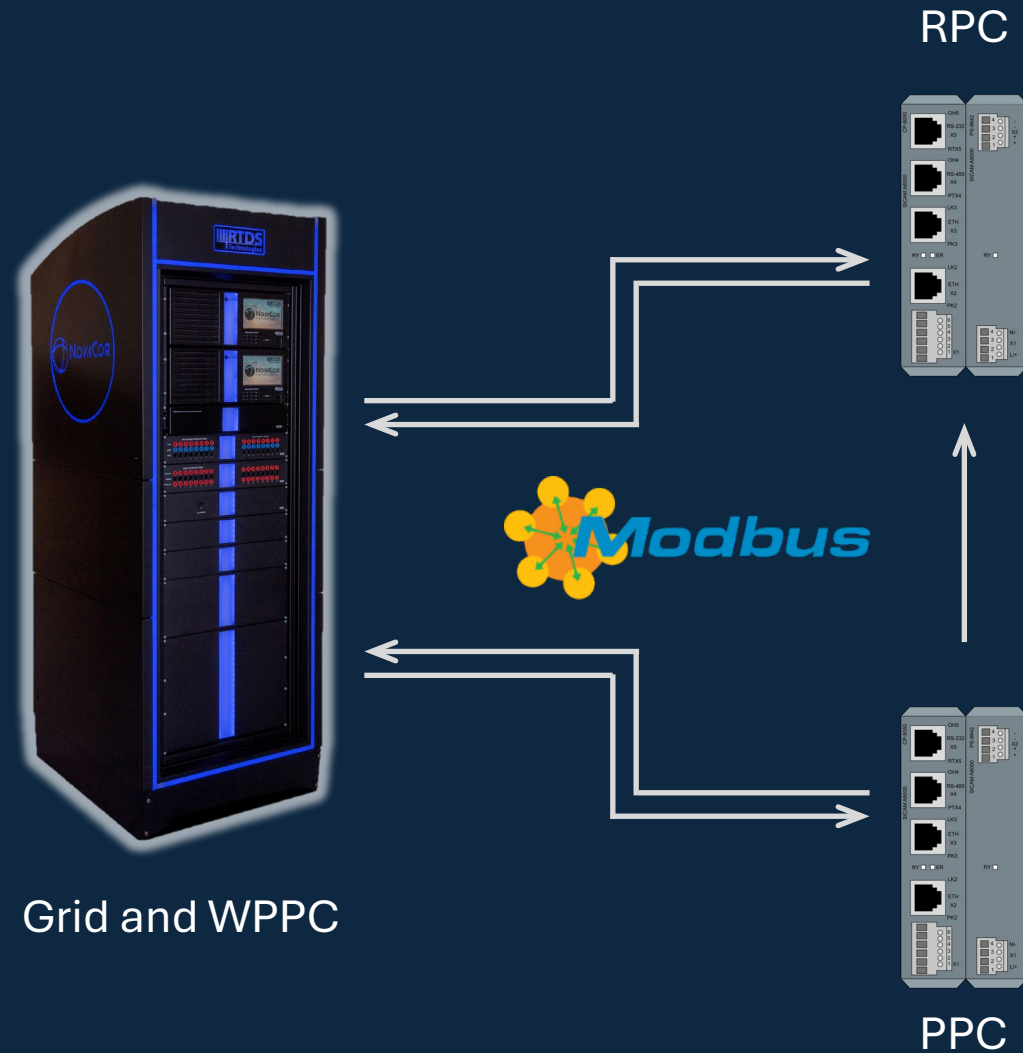
CHIL Simulation Results

- Communication delay noticeable in the reactive power response
- Higher overshoot due to communication delay to the WPPC
- Largest response deadtime remains below 150 ms
- Largest 5 % settling time remains below 1 s



Conclusion and Outlook

- Compliance with the UK national grid code validated in terms of reactive power requirements
- Coordinated control scheme validated under more realistic communication delays
- Switching logic implemented and validated using industrial controllers
- Future work may consider the WPPC as third industrial controller and the usage of a conventional PPC



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