Ancillary Services from Wind Farms

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Context

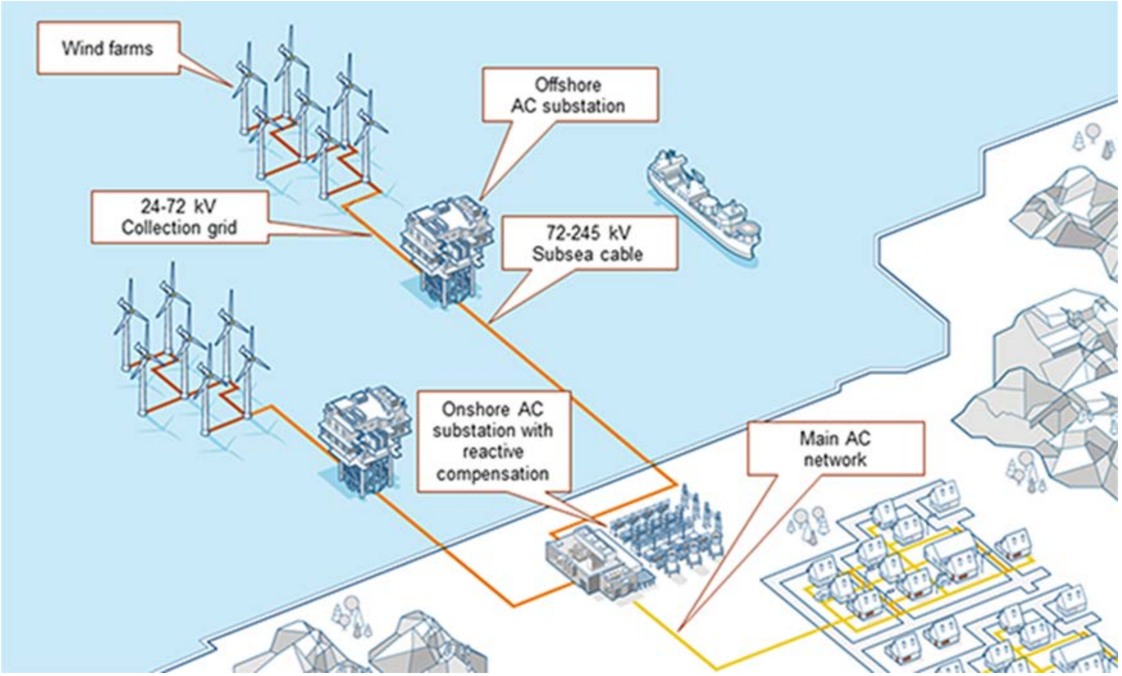
To provide full range of Ancillary Services requires

- Flexible operation of array
- Flexible operation of turbines
- Delivery by wind farm control
- Robustness to comms delays
- Array to act as virtual plant

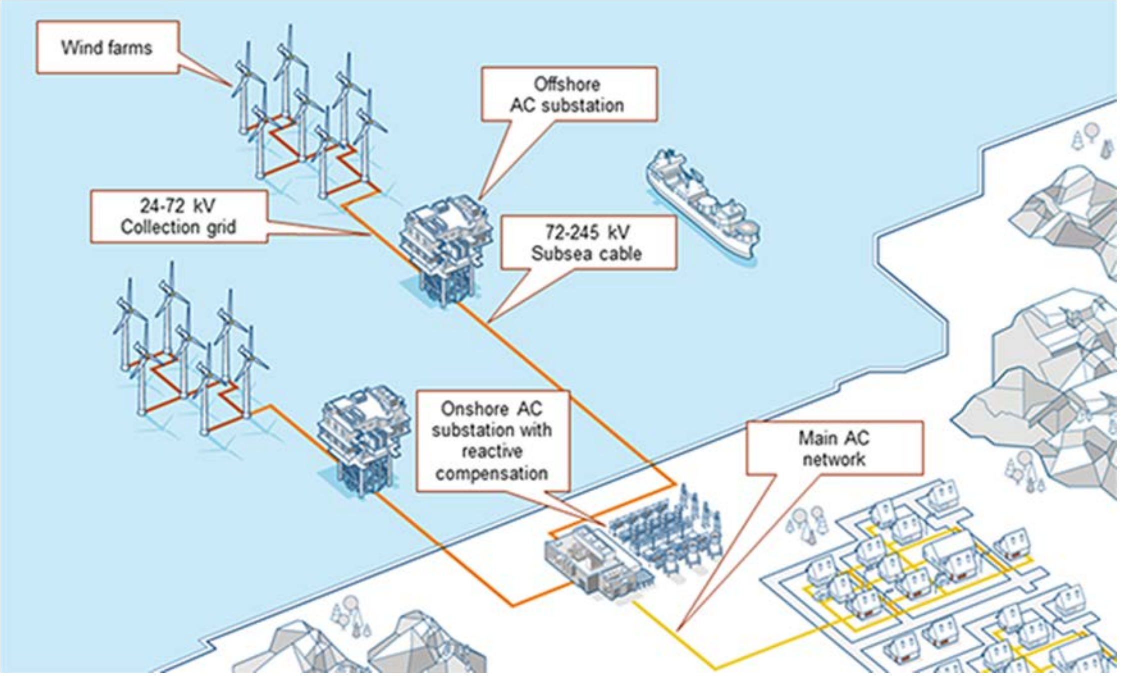
Context

Worst case scenario

- GW size array
- Far offshore
- HVDC connection-to-shore



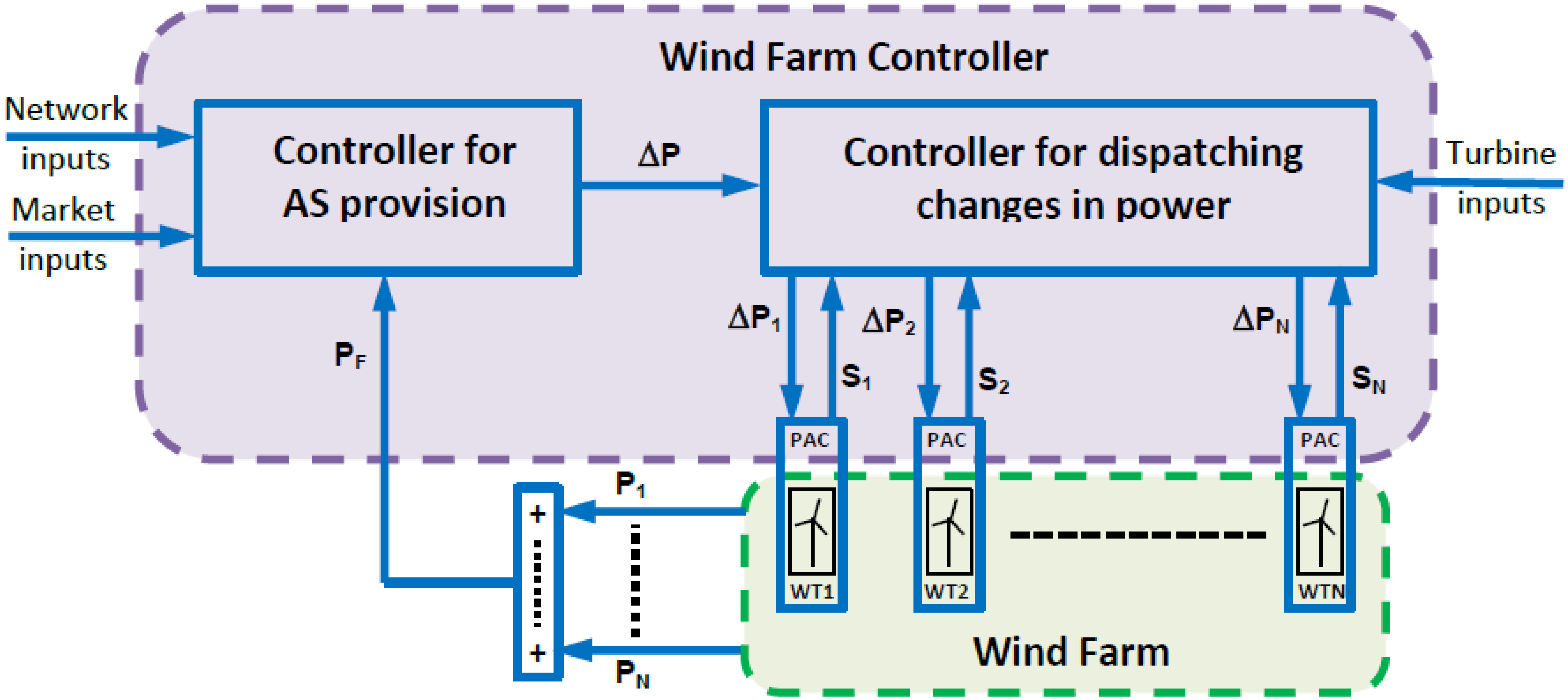
Wind Farm Control Structure



Wind Farm Control Structure

Ancillary Services are delivered by the controller

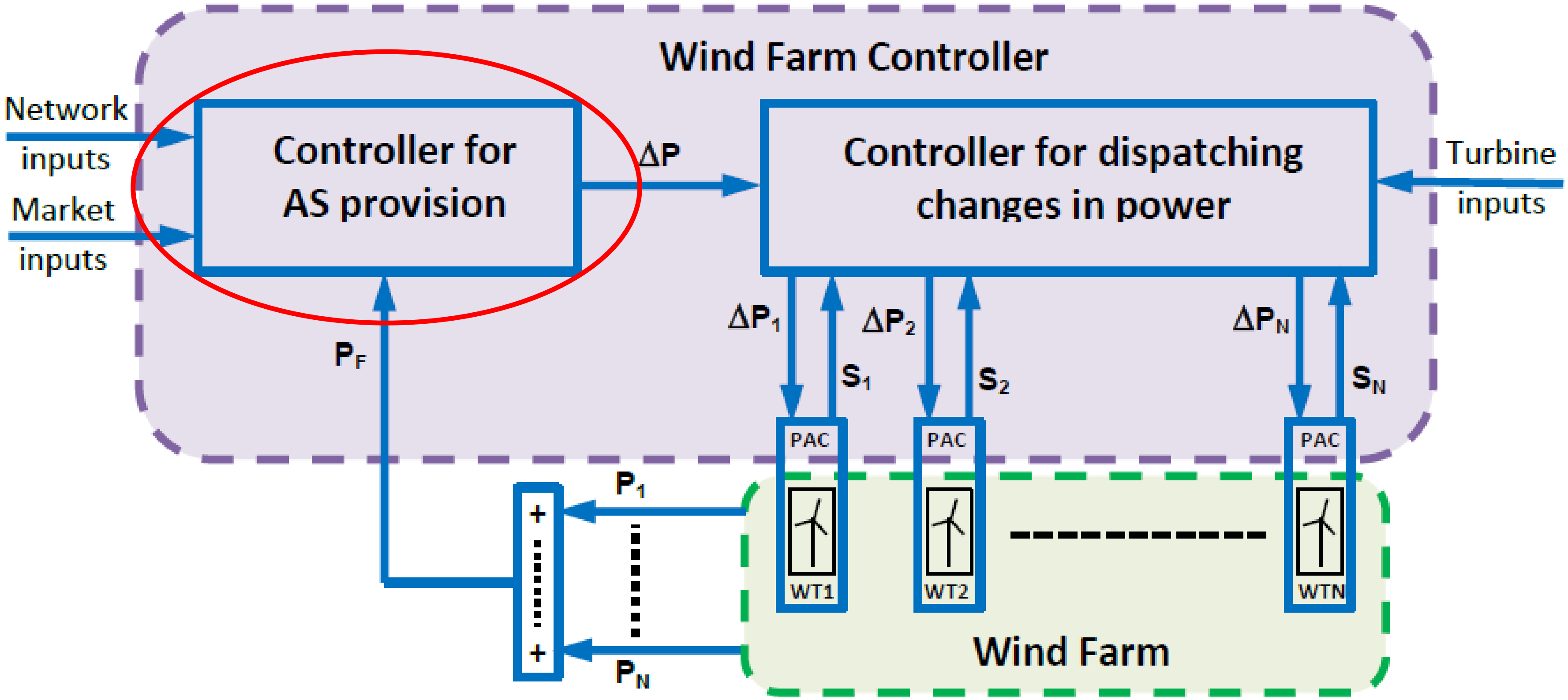
- Architecture provides full flexibility of operation
- It is distributed, hierarchical and scalable



Wind Farm Control Structure

Controller for AS provision

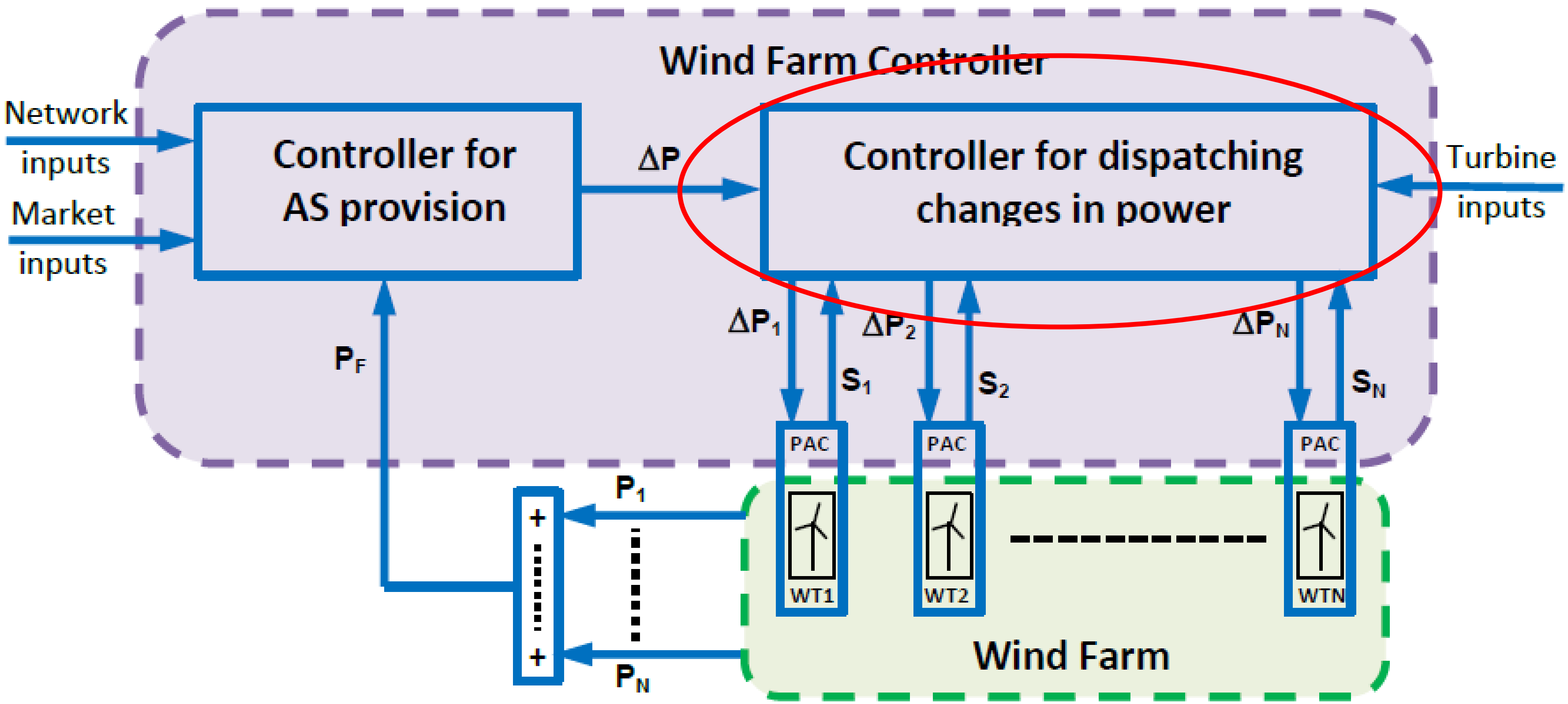
- Determines total change in power, **ΔP**, required
- May or may not depend on current output, $\mathbf{P_F}$



Wind Farm Control Structure

Controller for dispatching changes in power

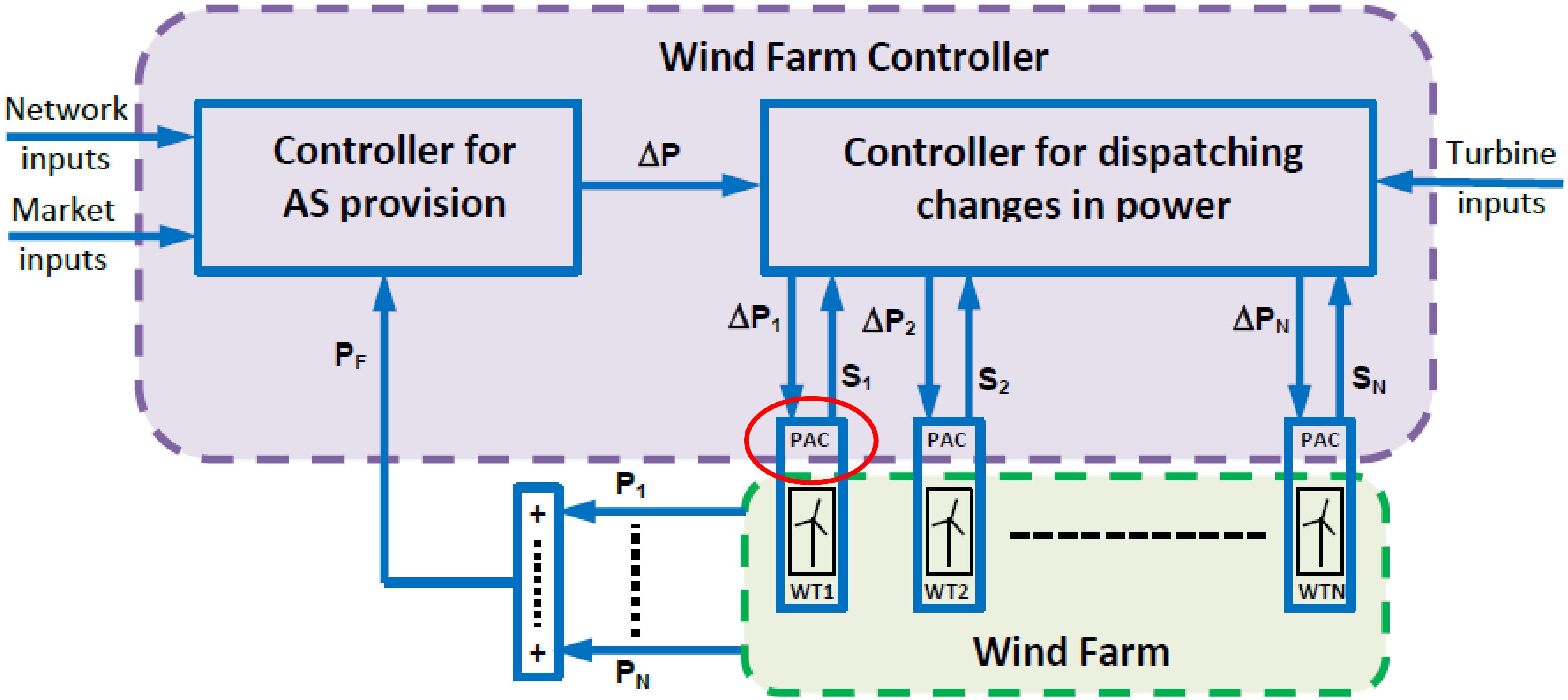
- Determines change in output, **ΔP_i**, required from each turbine



Wind Farm Control Structure

Power Adjusting Controller, **PAC**, is interface to turbine controller

- Adjusts output of turbine **i** by ΔP_i, as requested
- PAC passes back info on turbine state using flags, S_i



Wind Farm Control Structure

Power Adjusting Controller, **PAC**, is interface to turbine controller

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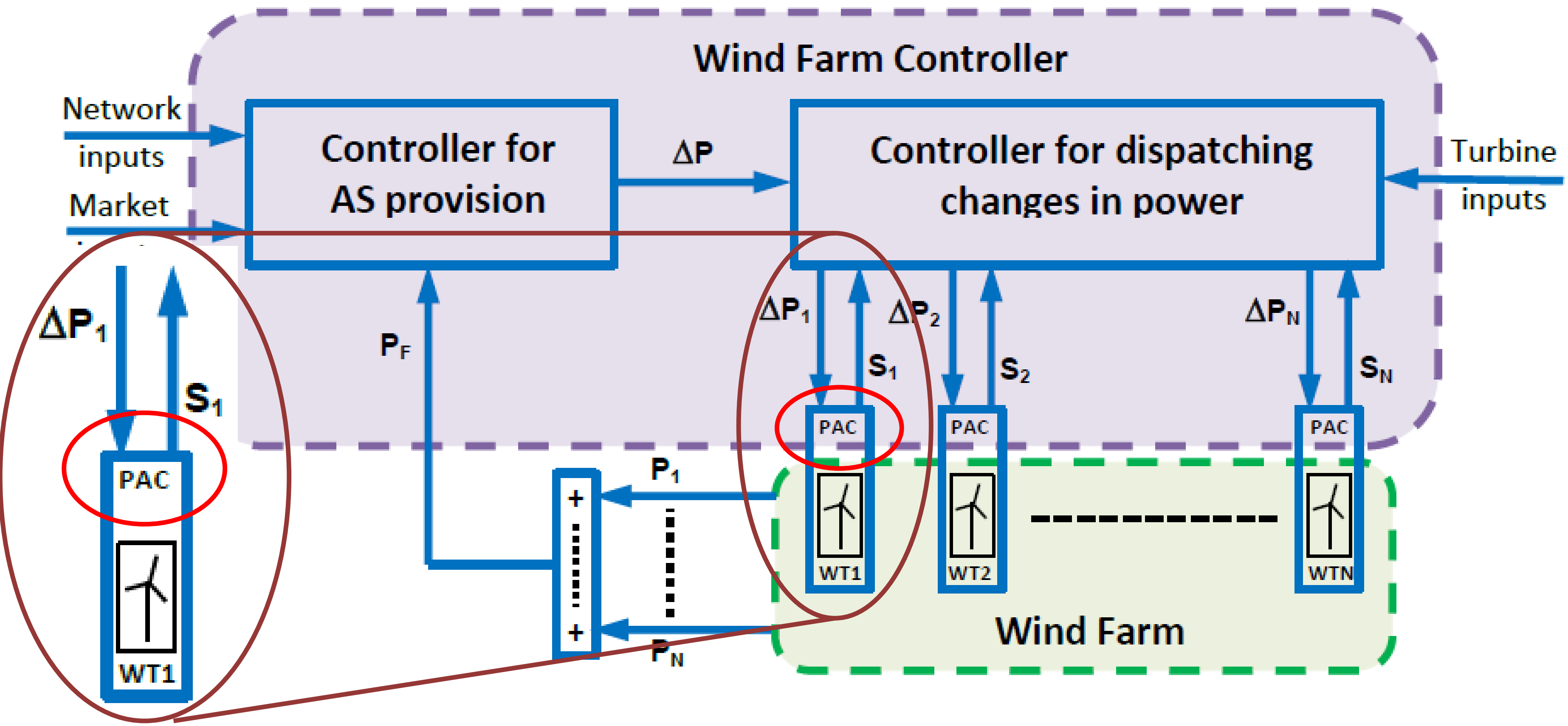
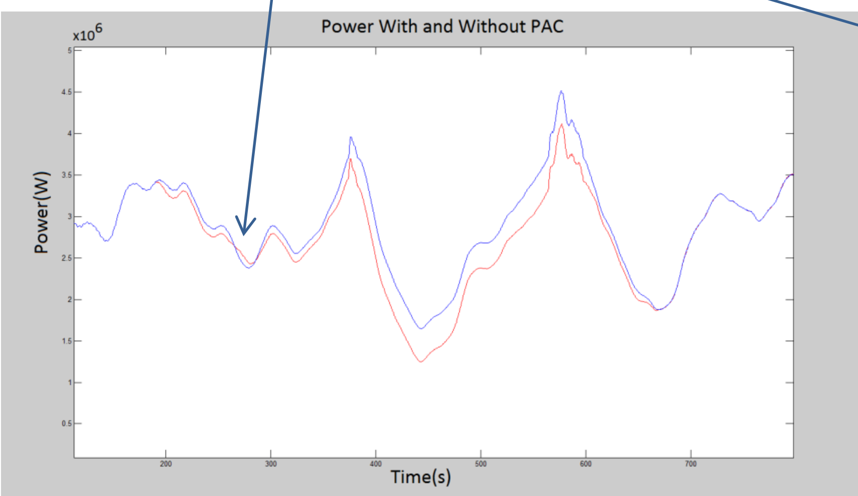


Wind Farm Control Structure

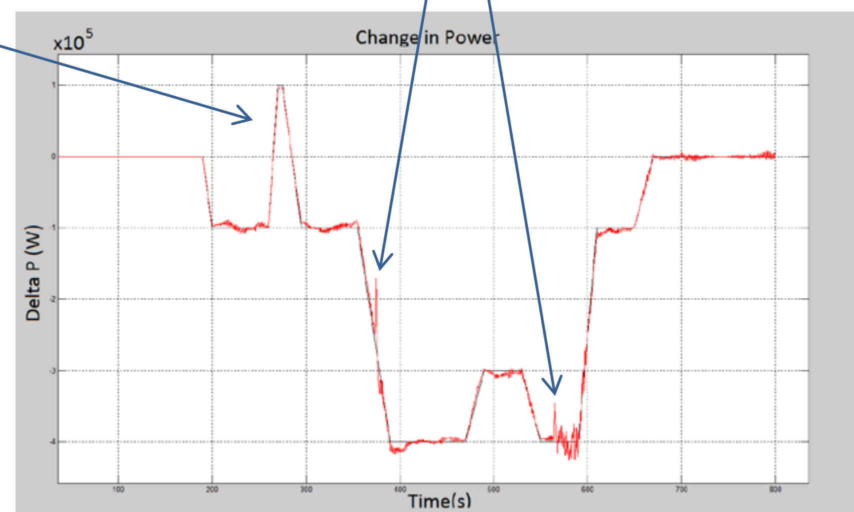
- 5MW wind turbine in 9m/s mean wind speed
- Output adjusted in increments of 100kW

Increase in output power

Full envelope controller mode switch



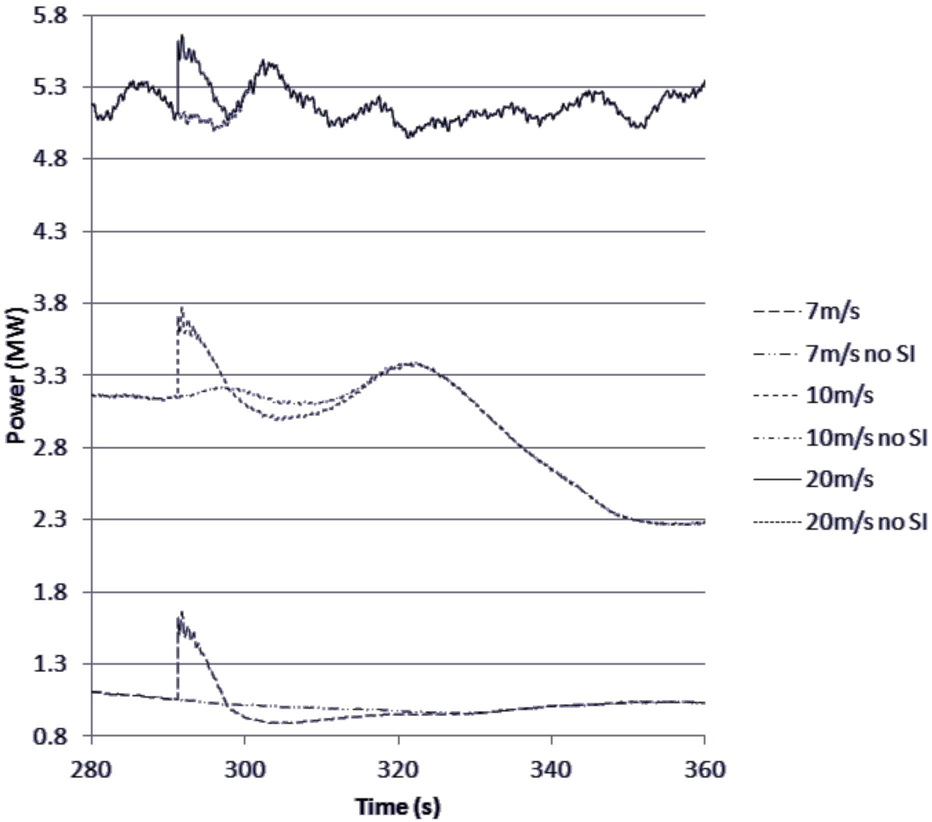
Power output with and without PAC



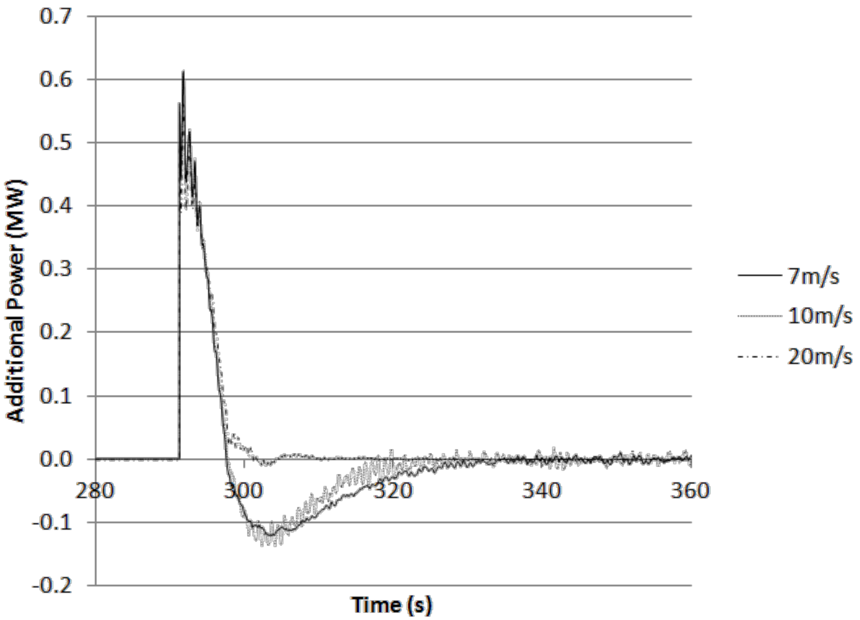
Difference in output with and without PAC

Wind Farm Control Structure

- Provision of synthetic inertia by PAC on 5MW wind turbine
- 7, 10 and 20m/s mean wind speed

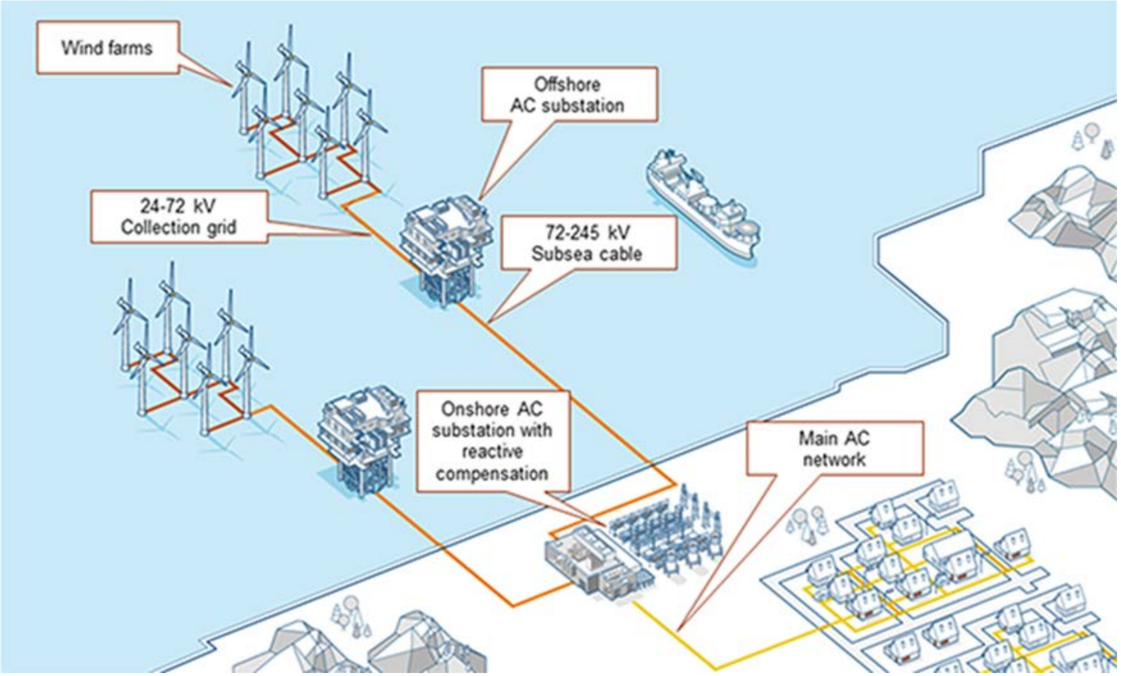


Absolute power outputs



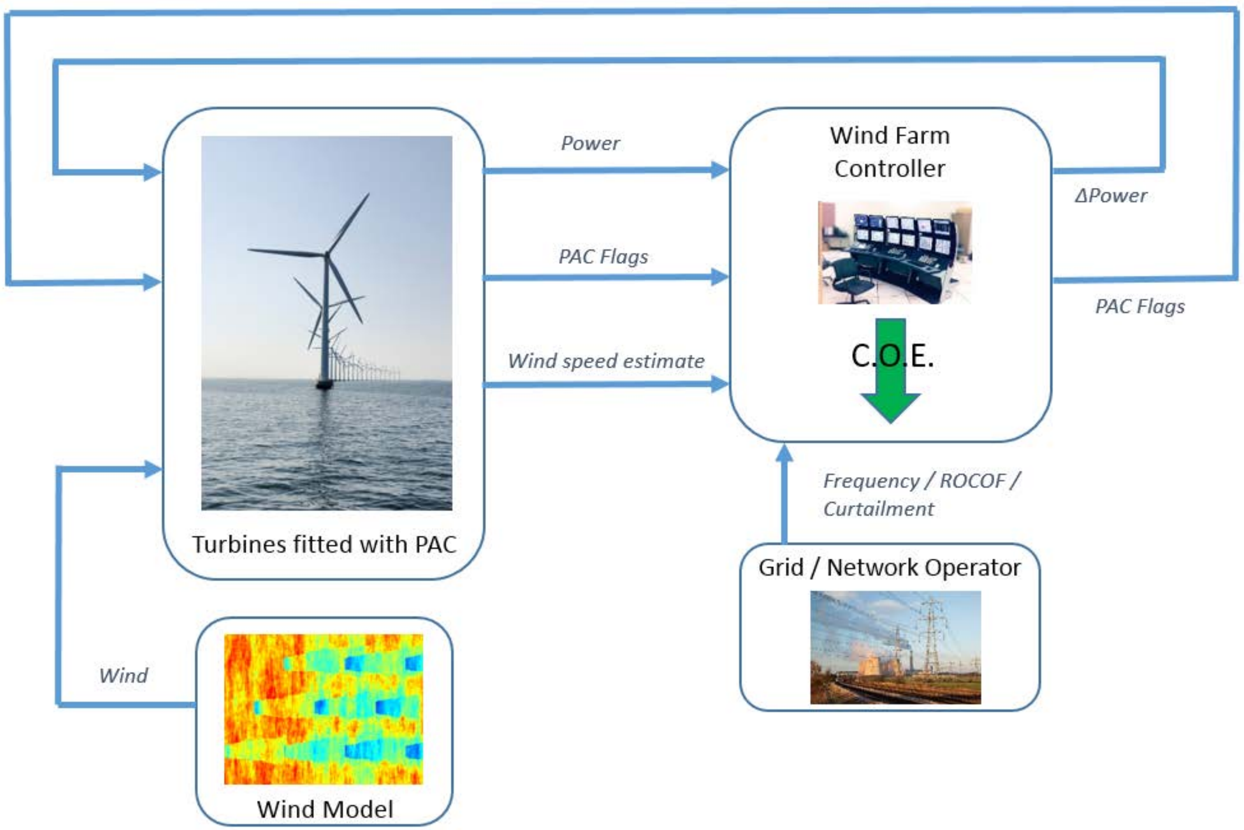
Relative power outputs

Wind Farm Simulation

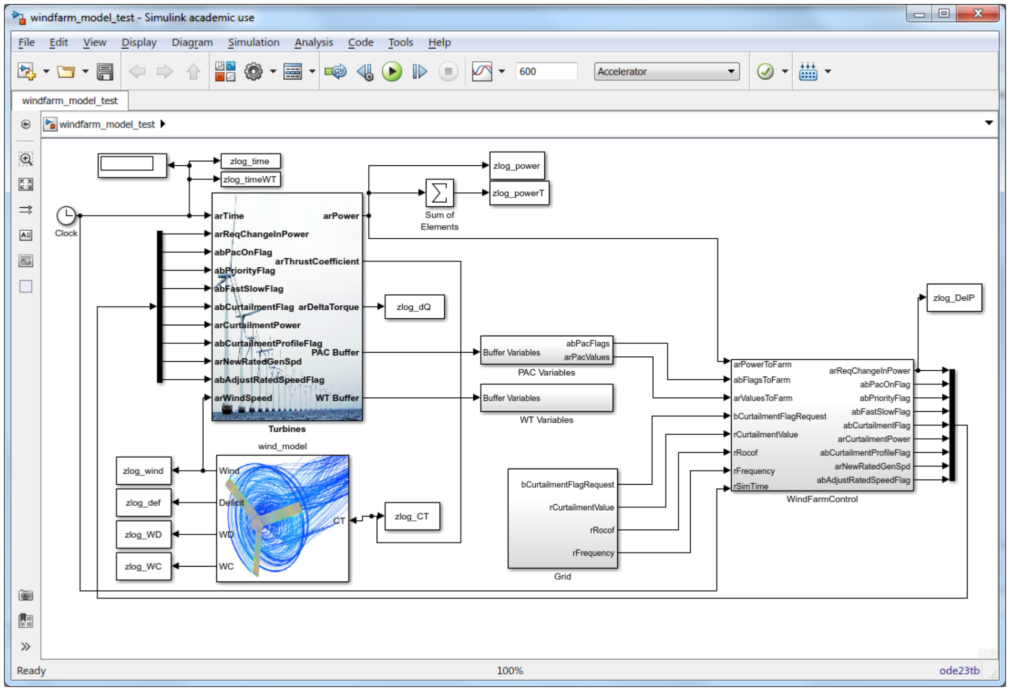


Wind Farm Simulation

- **StrathFarm**



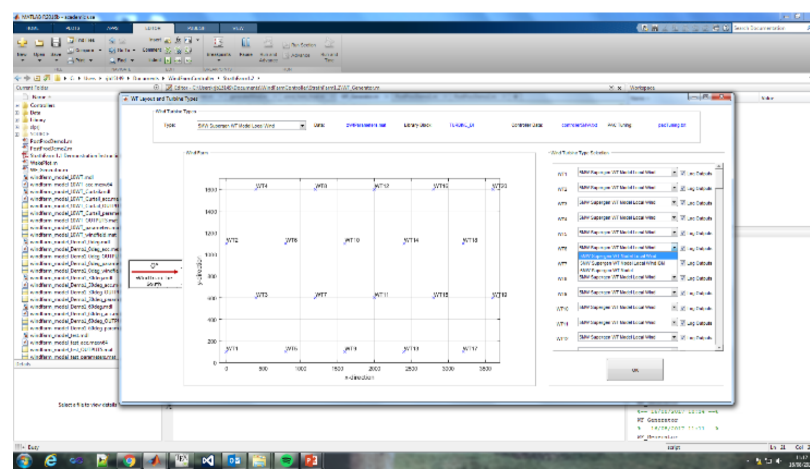
Wind Farm Simulation



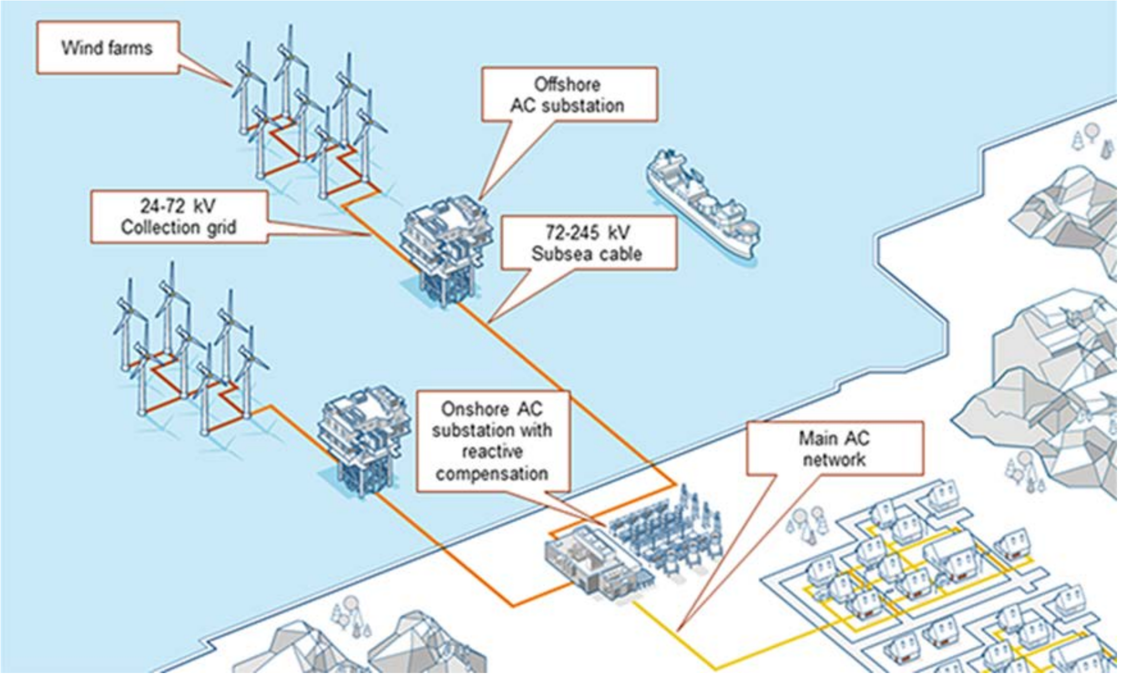
- Simulink model with compiled C++ elements
- Up to 100 turbines
- Run in real time on desk-top PC

Current simulation times (for 600s Simulation):

- 5WTs ~ 33s
- 20 WTs ~ 155s

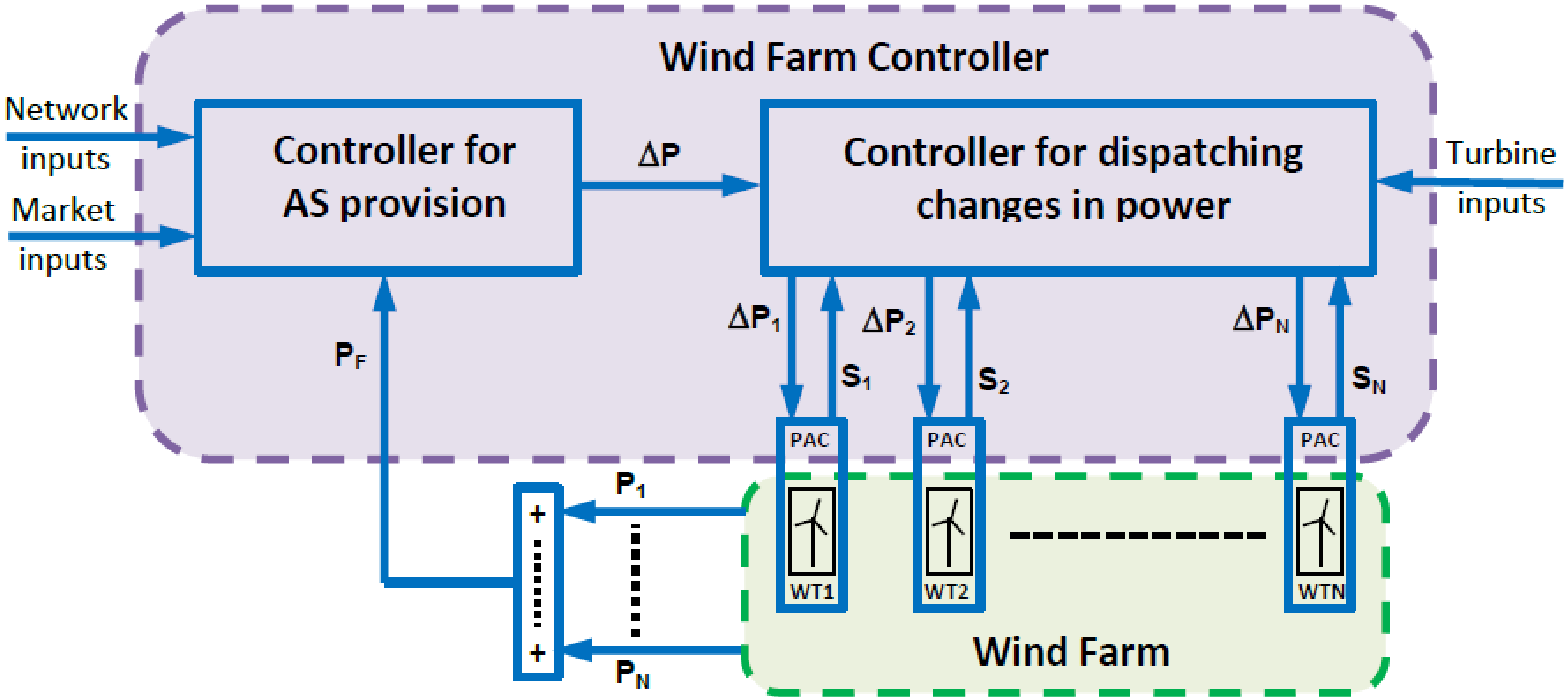


Farm Output Curtailment

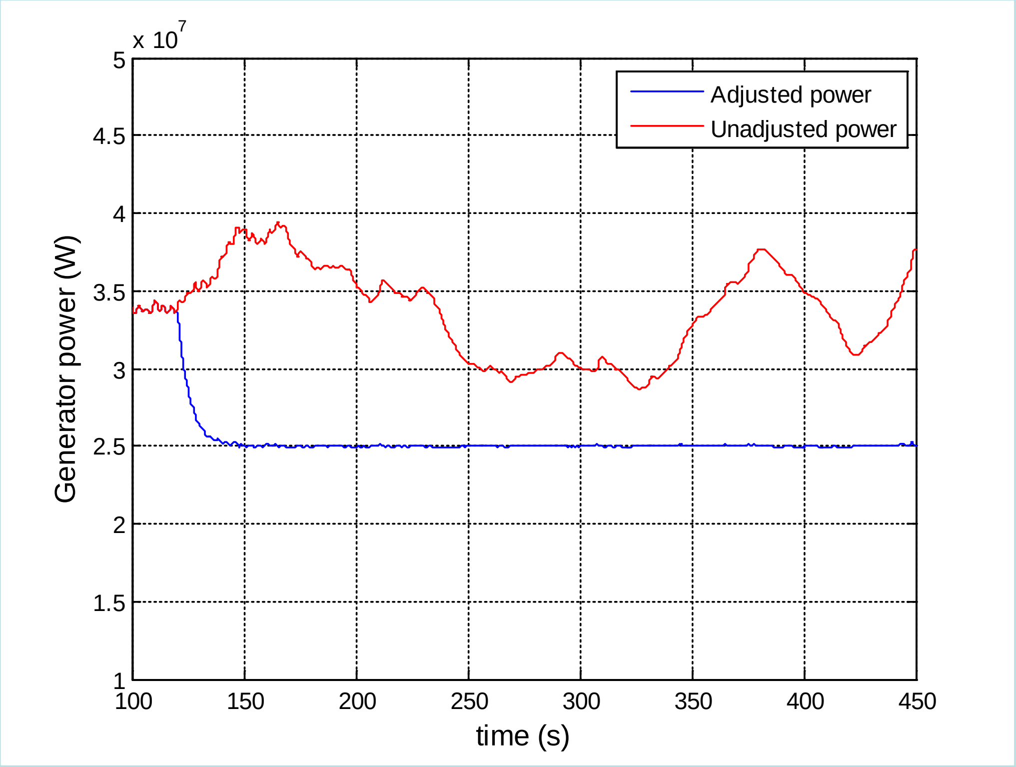


Farm Output Curtailment

- Controller for AS provision acts on ($\mathbf{P_0}$- $\mathbf{P_F}$)
- It has integral action
- Δ**P** is continuously updated to drive ($\mathbf{P_0}$- $\mathbf{P_F}$) to zero



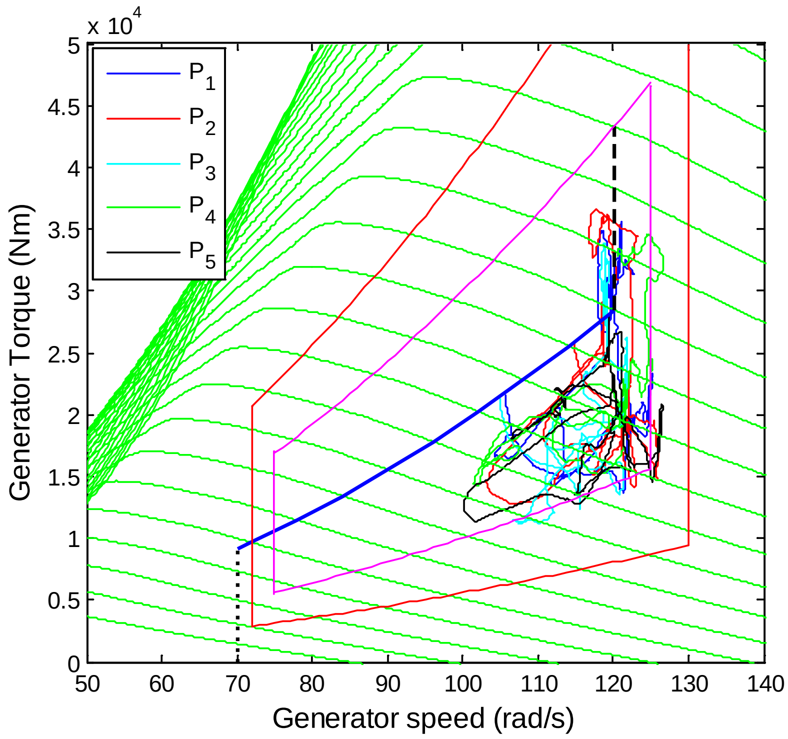
Farm Output Curtailment

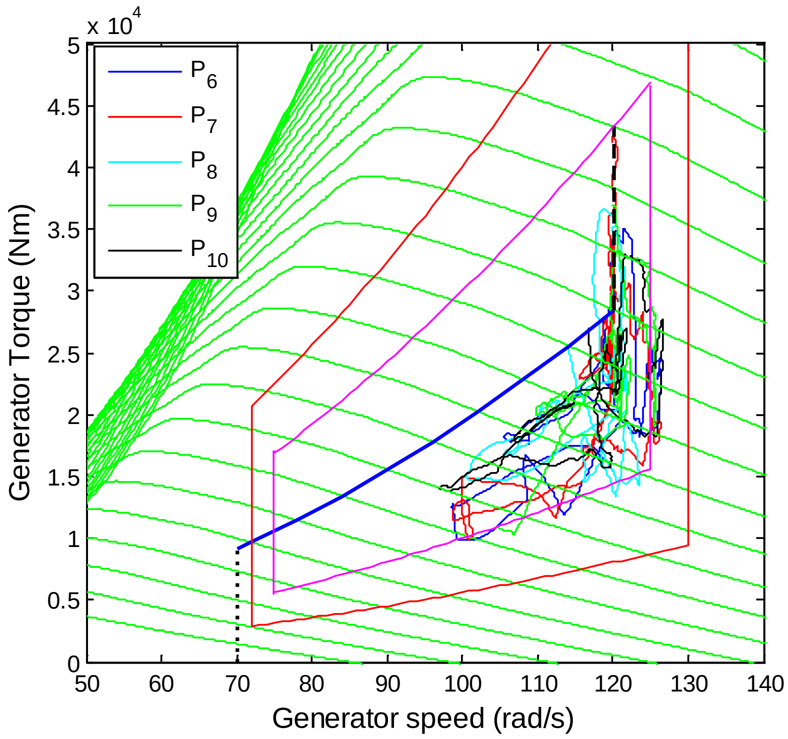


- Wind farm of 10x5MW turbines with mean wind speed of 10m/s.
- Farm output with and without curtailment

Farm Output Curtailment

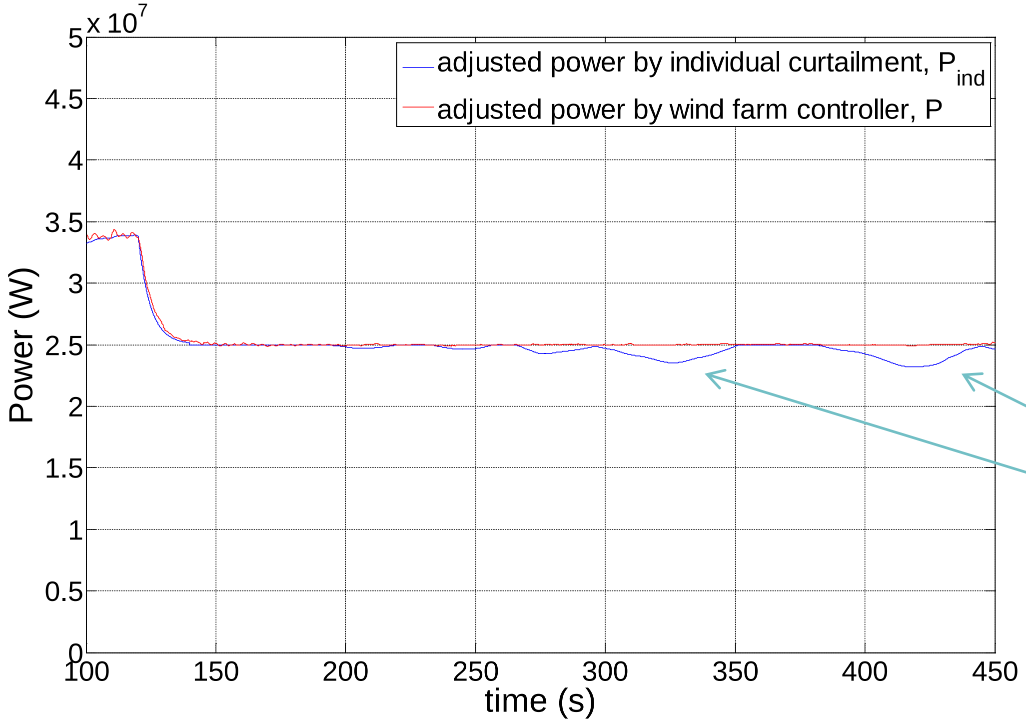
- Individual turbine behaviour





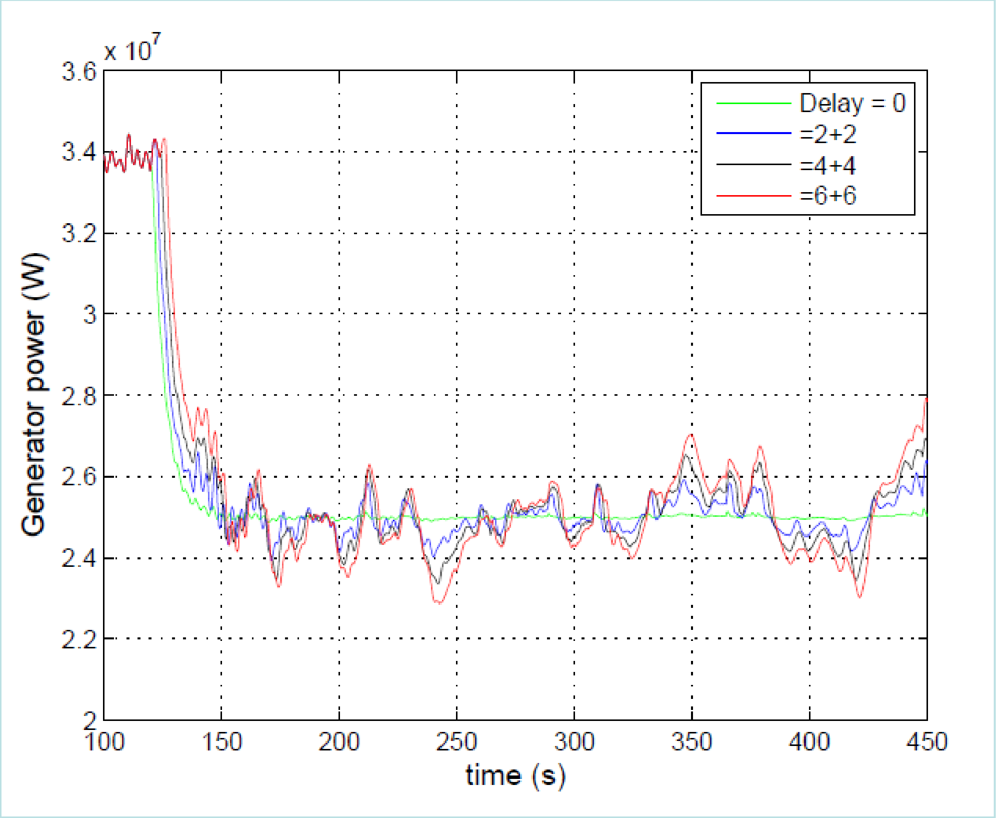
Farm Output Curtailment

- Wind farm output when turbines are curtailed individually.



Reduction in wind farm output

Farm Output Curtailment



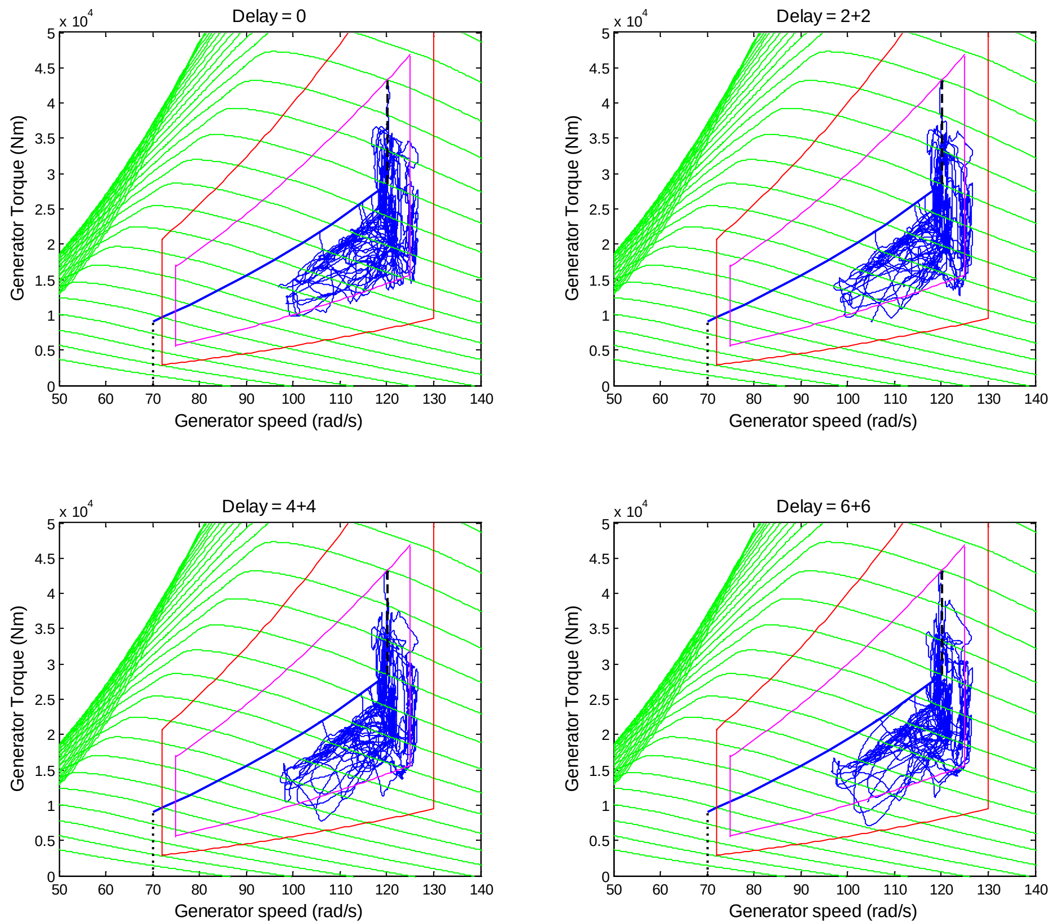
- Perturbations of power output about target of 25MW increases with time delay.
- Perturbations decrease as number of turbines in farm increases.

- Robustness to communication delays of 2, 4, and 6 seconds.

Farm Output Curtailment

No delay

2+2 delay

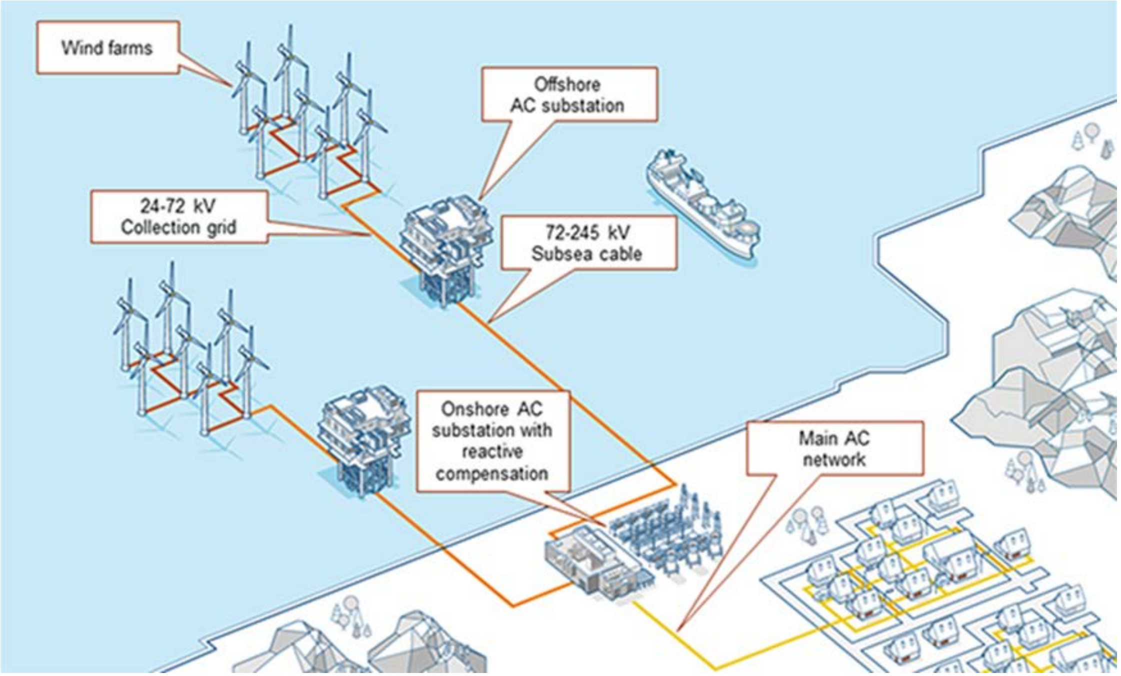


4+4 delay

6+6 delay

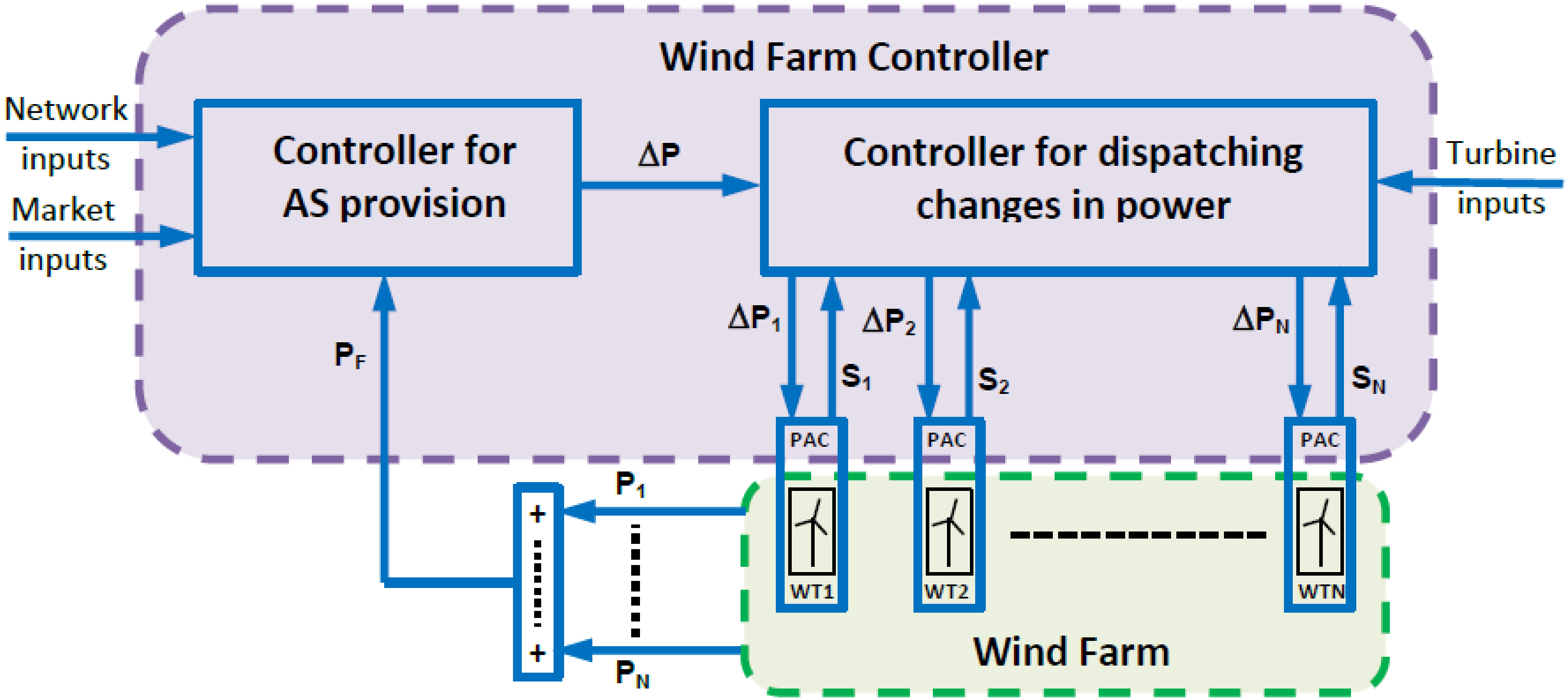
- Amber region safely cushions perturbations

Farm Level Frequency Support



Farm Level Frequency Support

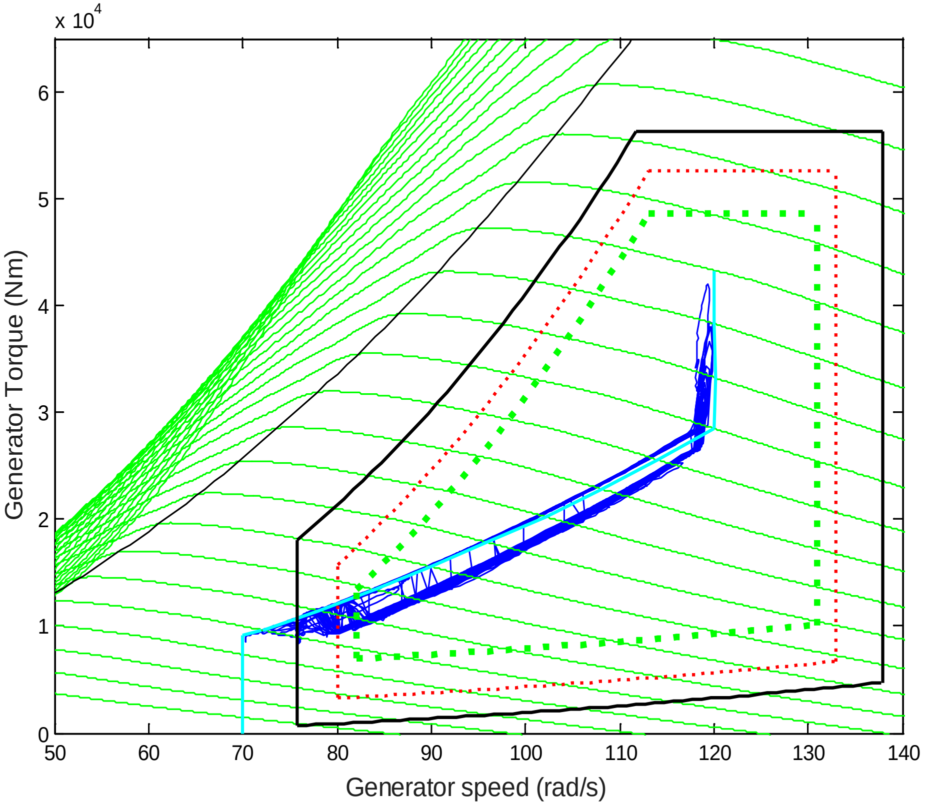
- Controller for AS provision does not act on $\mathbf{P_F}$
- $\mathbf{\Delta P}$ is continuously updated in response to grid frequency
- Provides both synthetic inertia and droop control



Farm Level Frequency Support

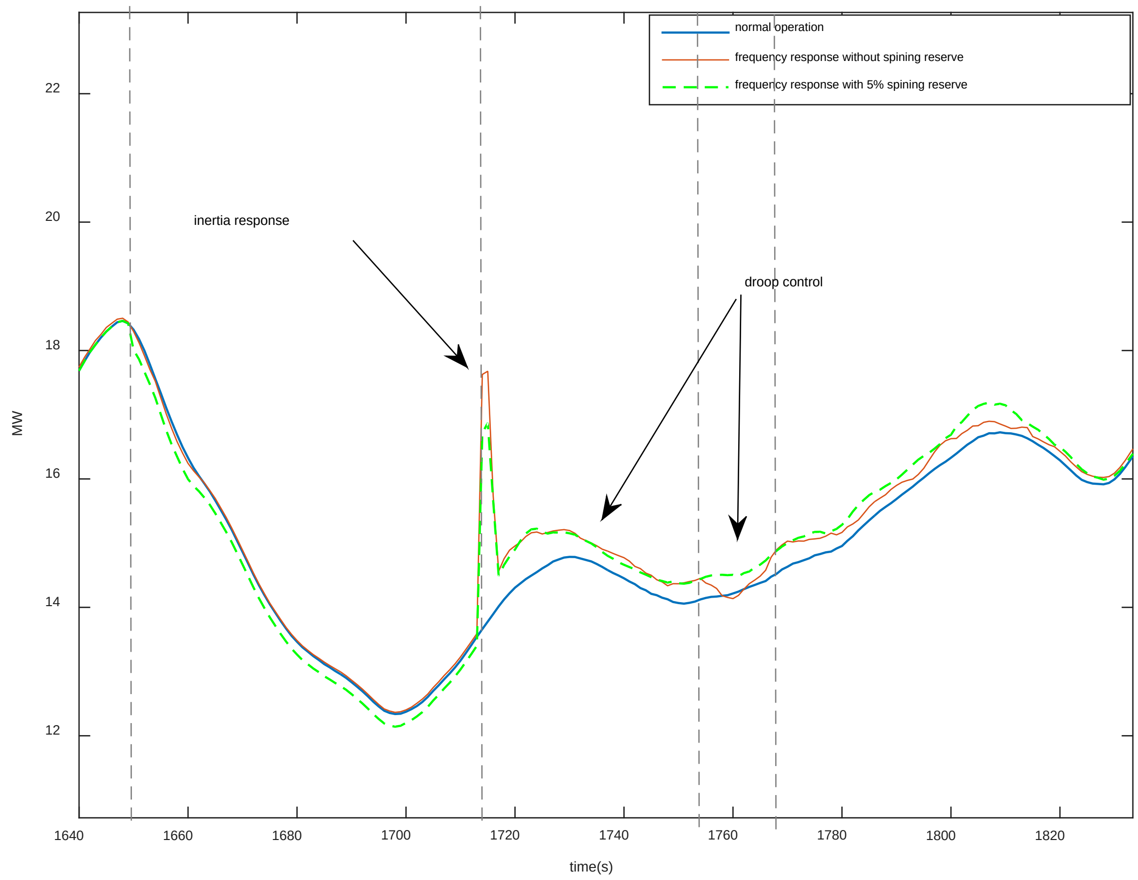
- Provision of ancillary services at farm level

- 10x5MW turbines in 2 columns of 5
- Mean wind speed ~ 8m/s
- Turbulence ~10%
- Requested reserve ~ 2MW



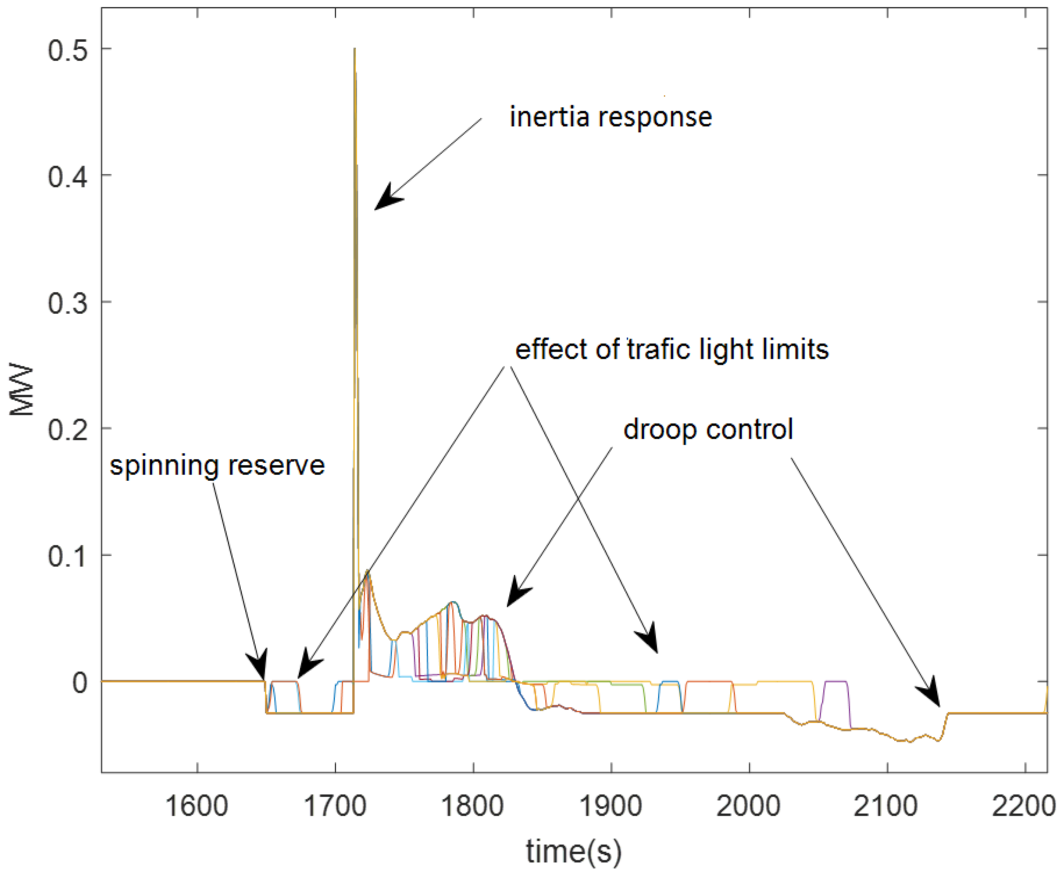
Provision of reserve power

Farm Level Frequency Support



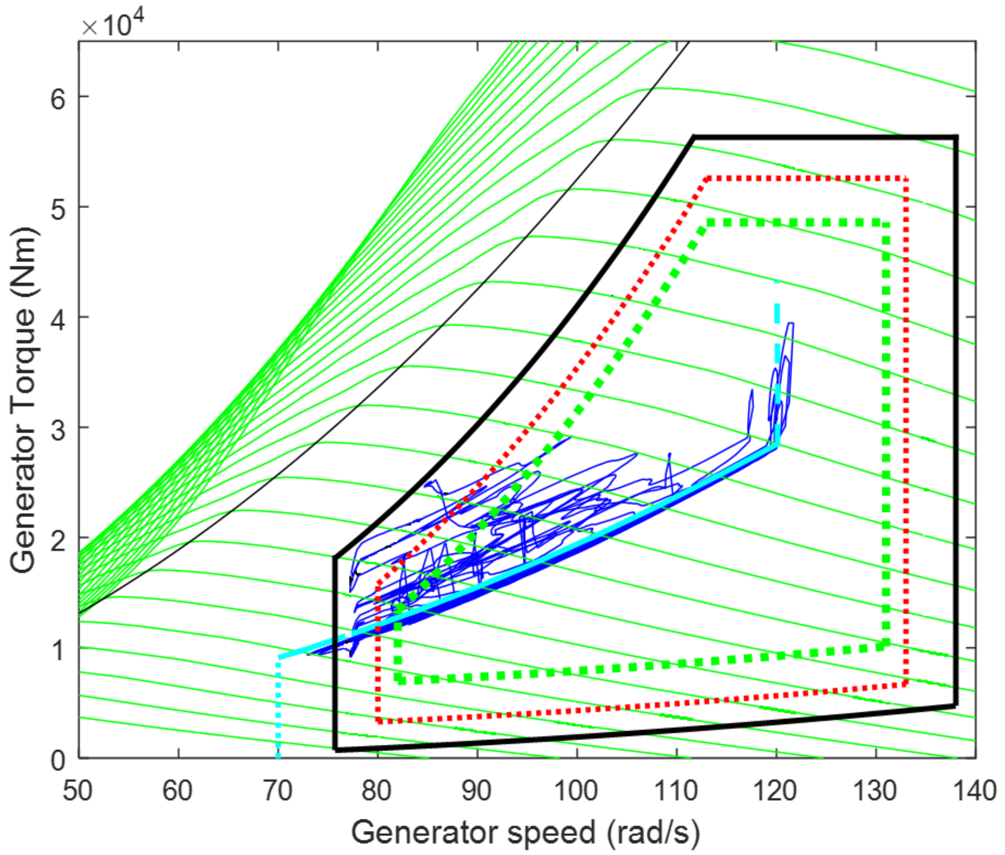
- Wind farm provision of frequency support with/without 2MW curtailment

Farm Level Frequency Support



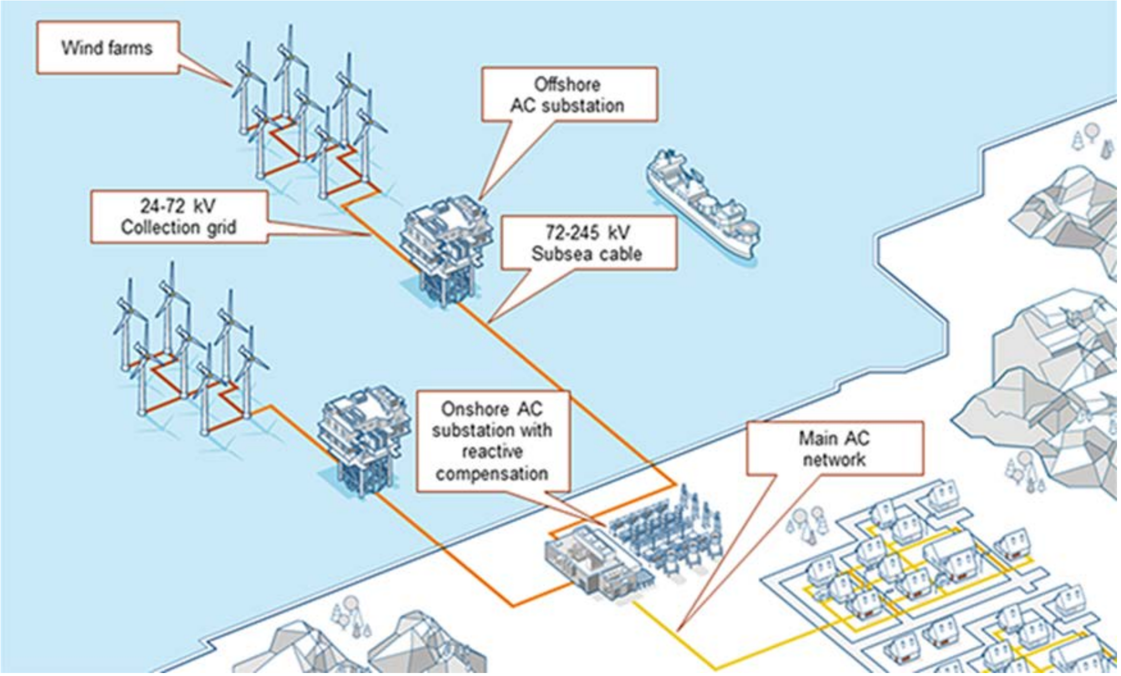
- Change in power for each turbine (with 2MW curtailment)
- Cross-compensation between turbines (needed as wind speed low)

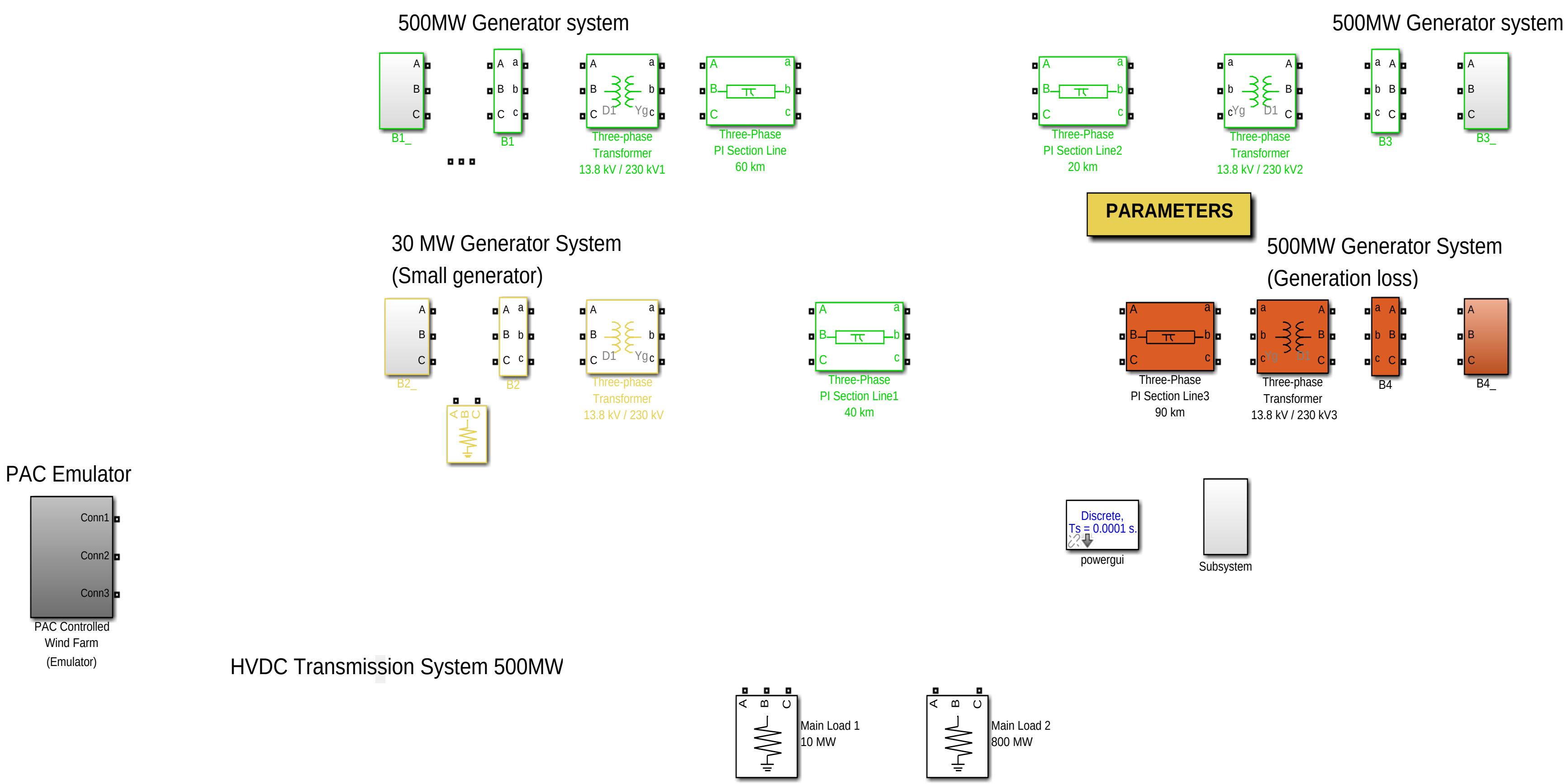
Farm Level Frequency Support



- Operation of each turbine

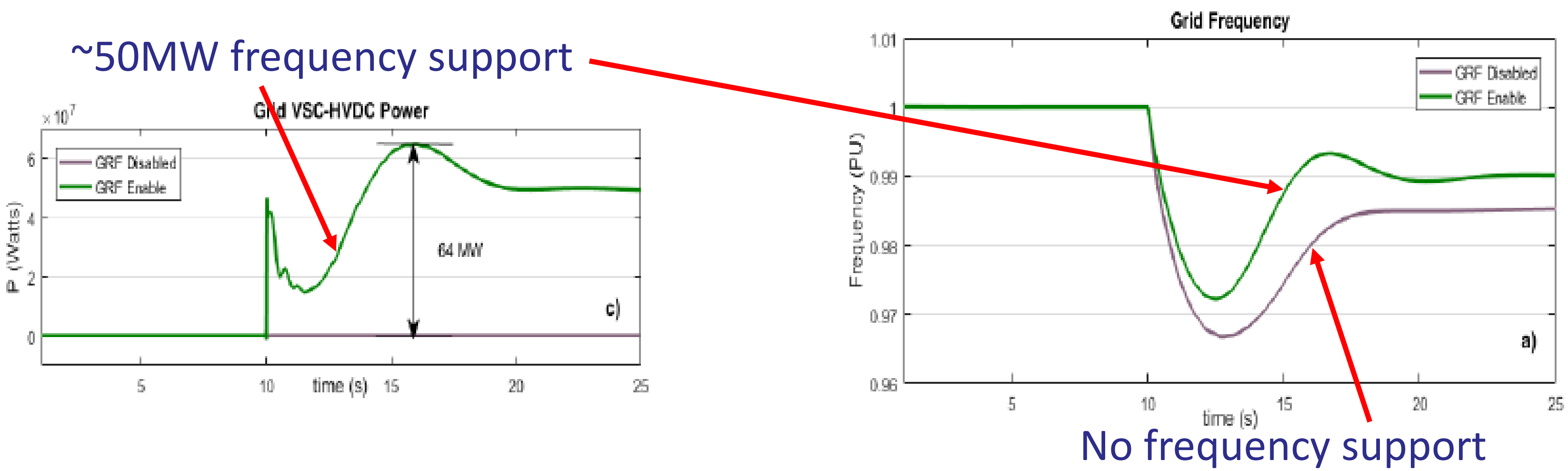
Virtual Conventional Plant




500MW Generator system
B1_
B1
Three-phase Transformer 13.8 kV / 230 kV1
Three-Phase PI Section Line 60 km
Three-Phase PI Section Line2 20 km
Three-phase Transformer 13.8 kV / 230 kV2
B3
B3_
500MW Generator system
PARAMETERS
30 MW Generator System
(Small generator)
B2_
B2
Three-phase Transformer 13.8 kV / 230 kV
Three-Phase PI Section Line1 40 km
500MW Generator System
(Generation loss)
Three-Phase PI Section Line3 90 km
Three-phase Transformer 13.8 kV / 230 kV3
B4
B4_
PAC Emulator
Conn1
Conn2
Conn3
PAC Controlled Wind Farm (Emulator)
Discrete, Ts = 0.0001 s.
powergui
Subsystem
HVDC Transmission System 500MW
Main Load 1 10 MW
Main Load 2 800 MW

Virtual Conventional Plant

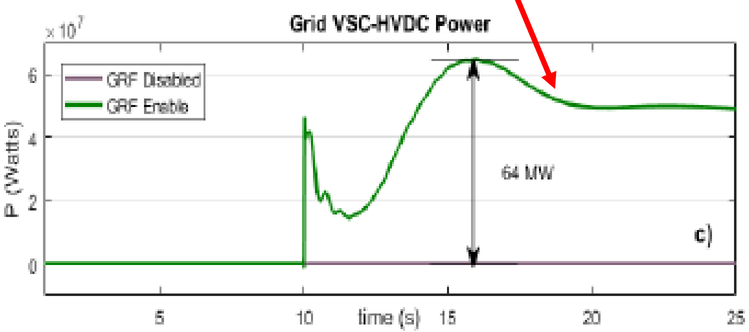
- Primary response provided by virtual plant

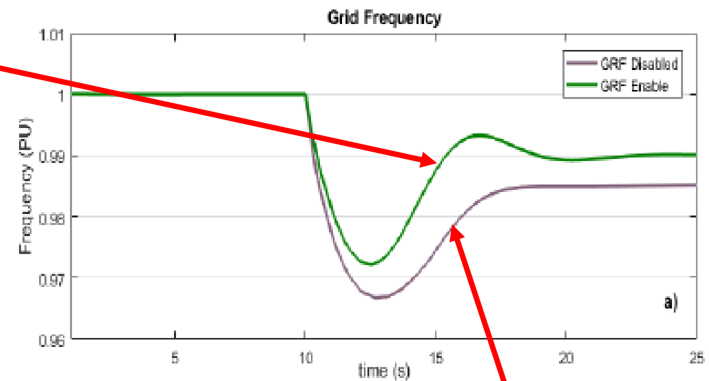


Virtual Conventional Plant

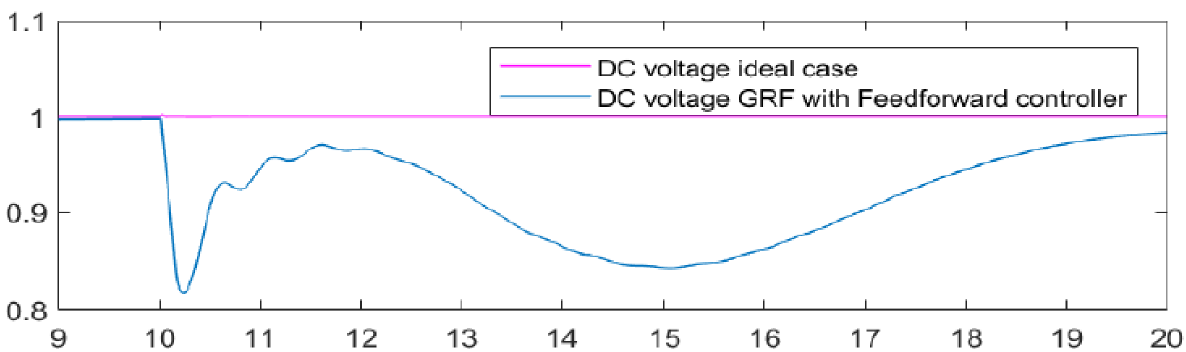
- Virtual plant with communication delay of 150ms

~50MW frequency support from array





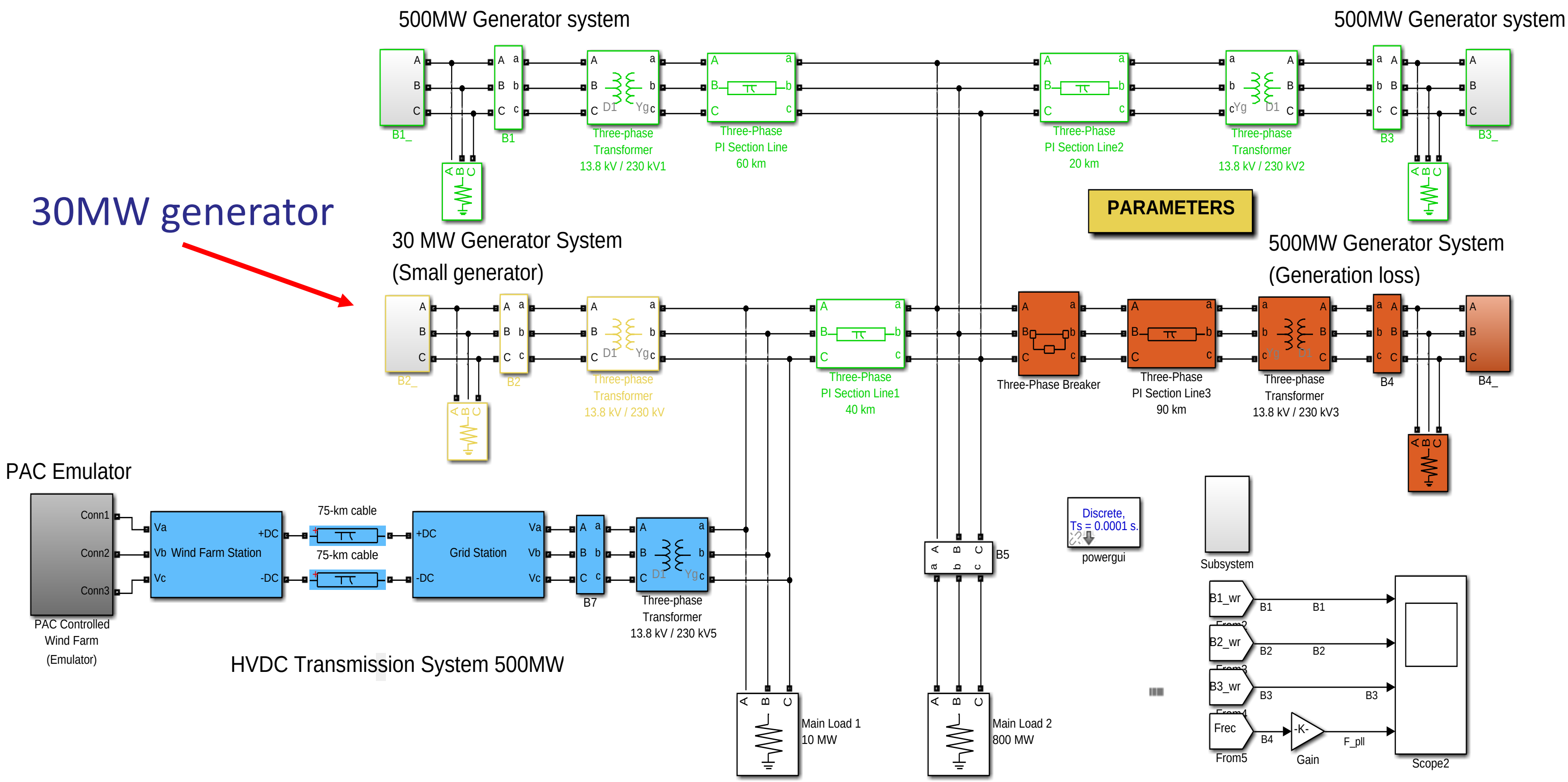
No frequency support from array



- DC voltage drop due to energy extraction

Virtual Conventional Plant

- Shorter delay reduces voltage drop
- Generator-response following control (GRP)



Virtual Conventional Plant

Generator-response following concept

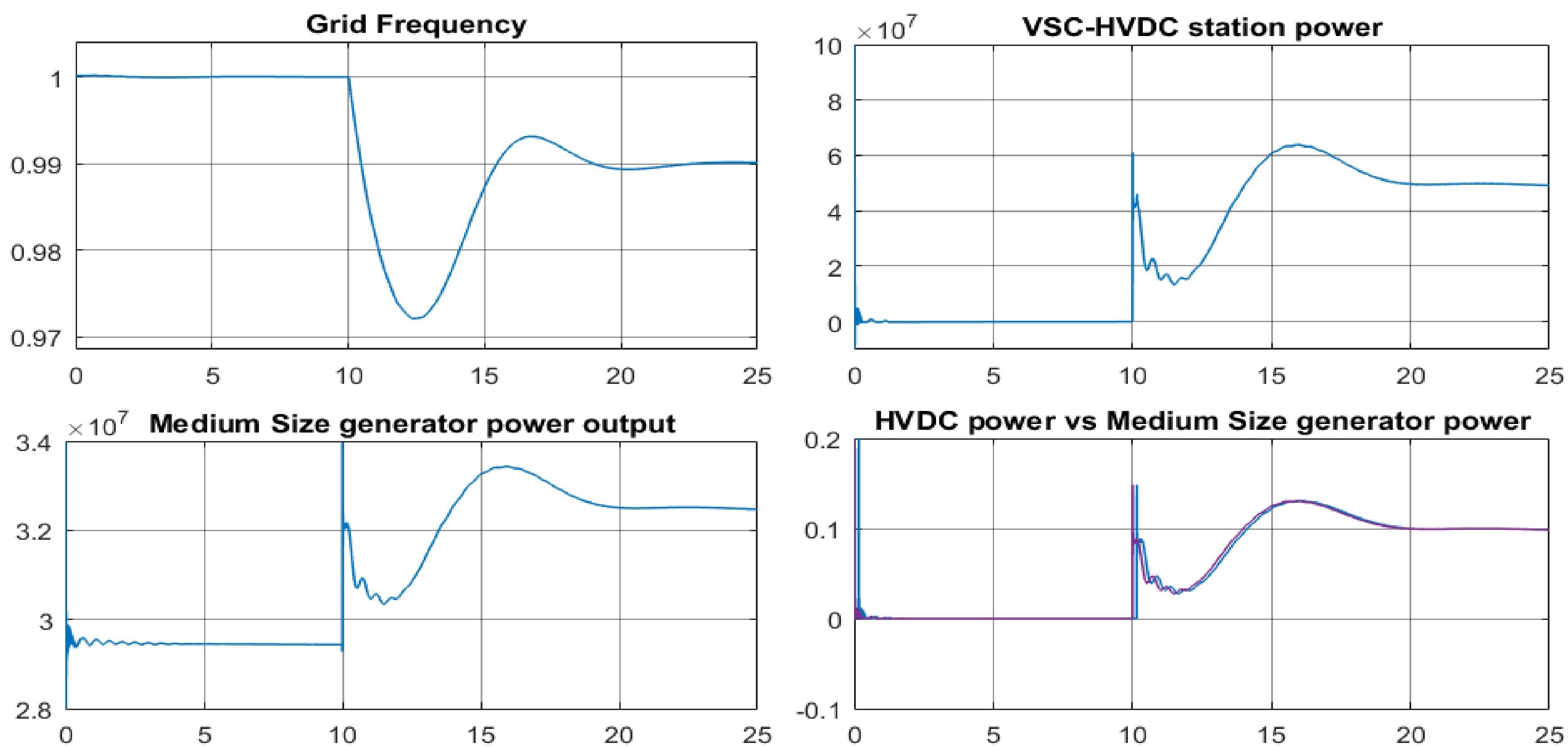
- Fully instrumented small/medium synchronous generator is connect at the Point of Connection of the wind farm
- Power output of the wind farm is slaved to follow the output of the synchronous generator using the wind farm controller
- When the small/medium synchronous generator provides Ancillary Services, then so does the wind farm, albeit scaled-up

Potential advantages

- No direct power frequency measurements to reduce delays
- Provides a full range of Ancillary Services, inertia, governor-droop control, reserve, curtailment etc.
- Grid Code Compliant

Virtual Conventional Plant

- GRF with communications delay of 150ms
- Feedforward control applied to HVDC sub-station
- Stability of grid is not compromised



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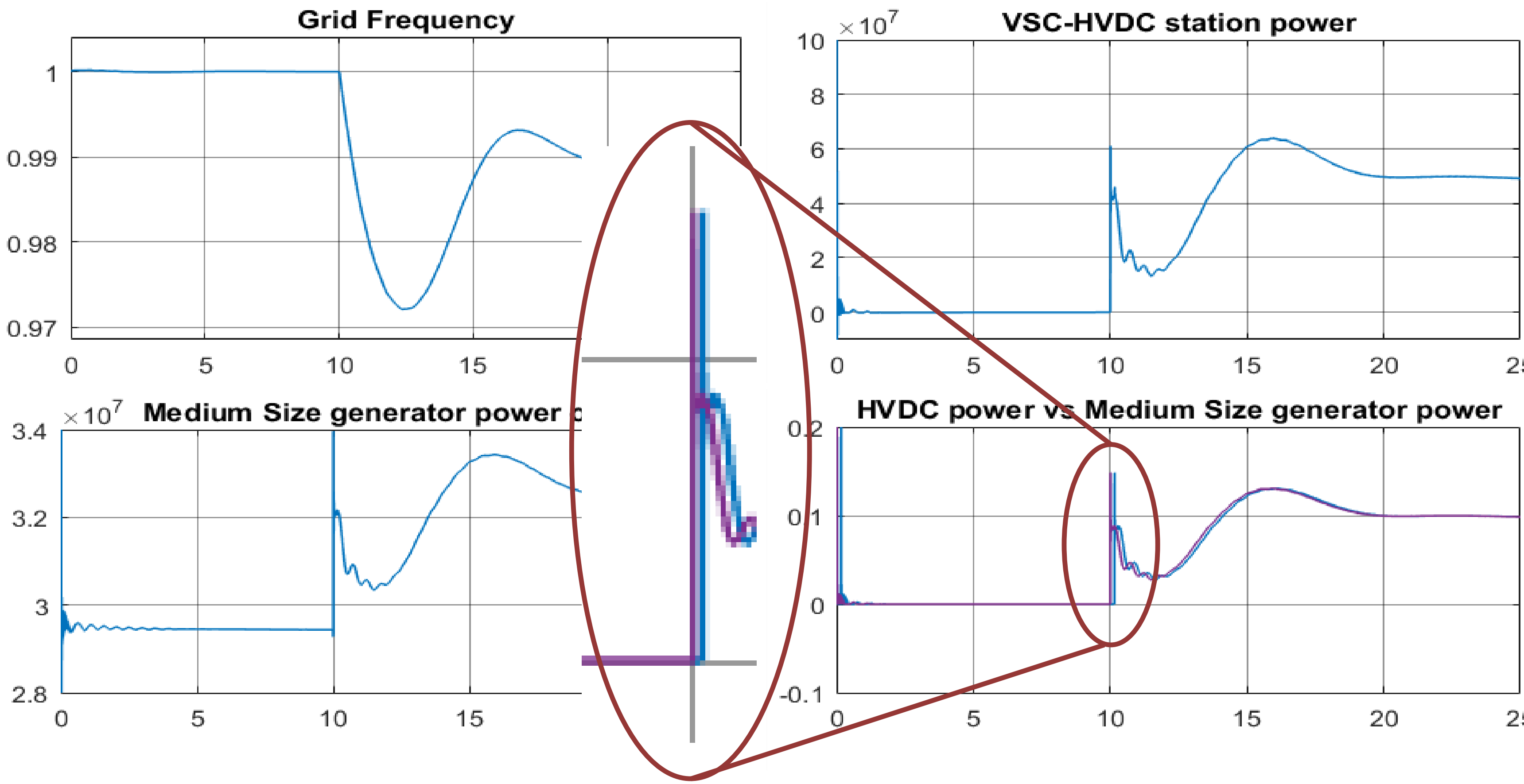
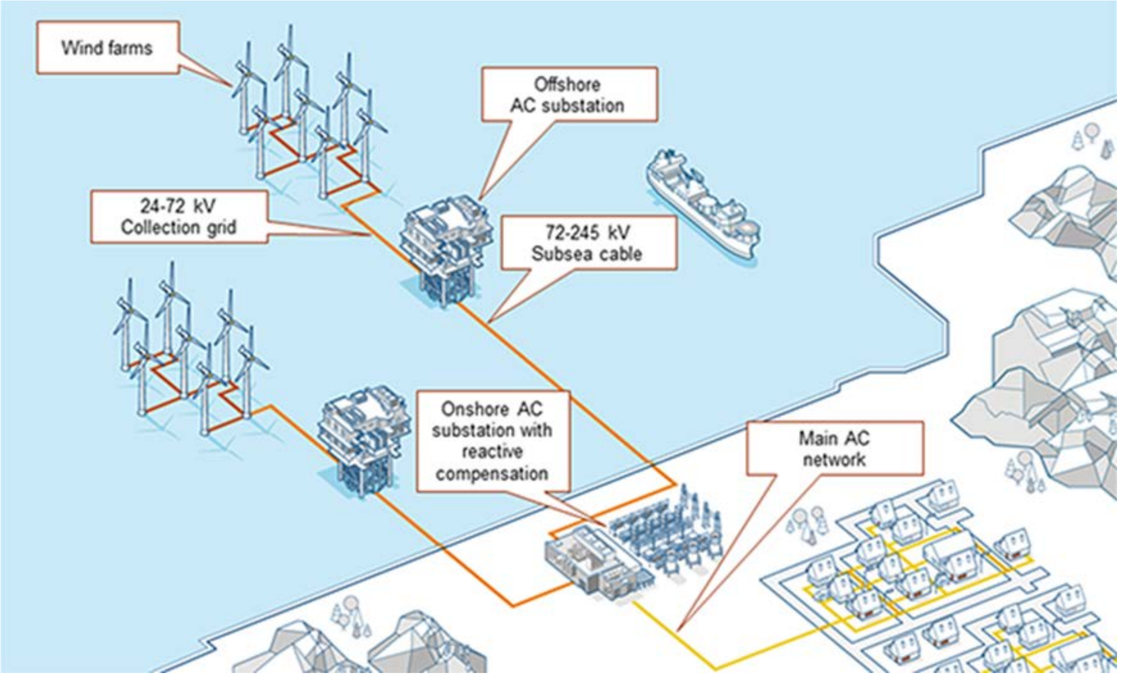


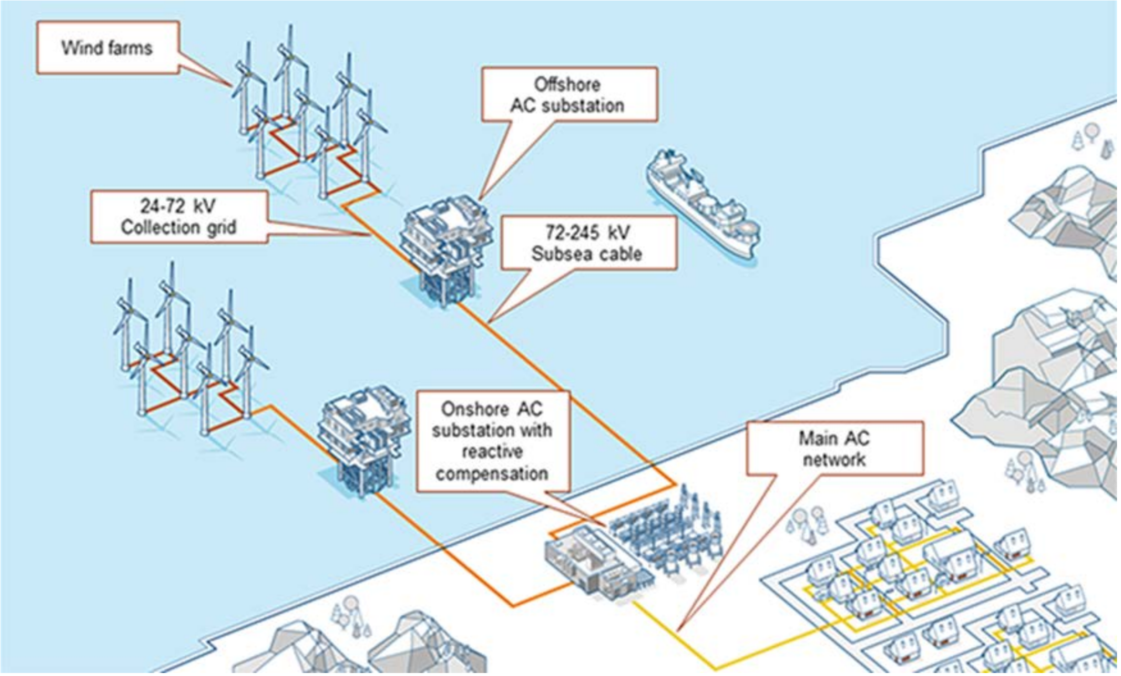
Conclusion


Wind farms
Offshore AC substation
24-72 kV Collection grid
72-245 kV Subsea cable
Onshore AC substation with reactive compensation
Main AC network

Conclusion

Provision of full range of Ancillary Services possible at wind farm level

Thank You



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