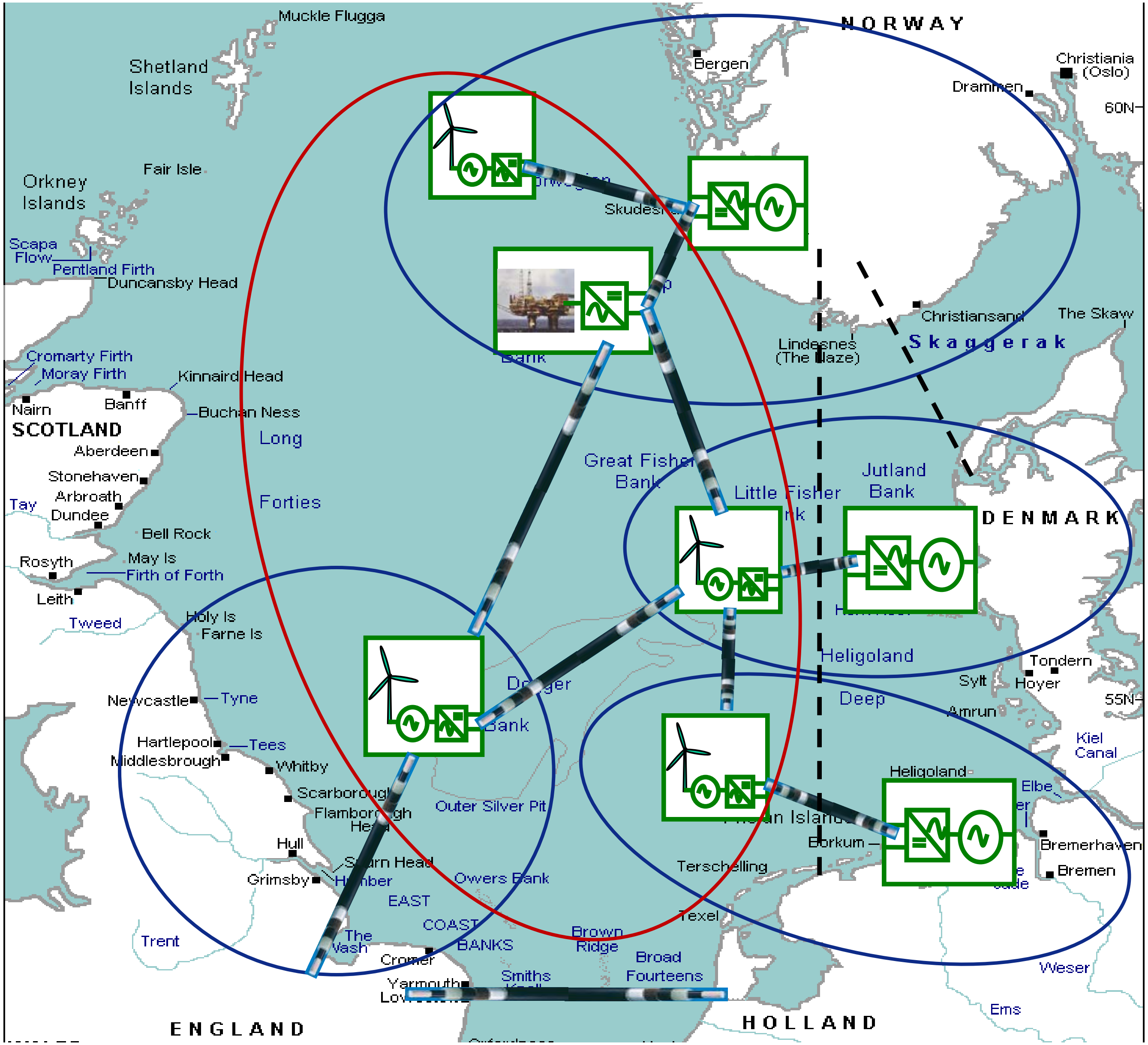
NTNU

Control of VSC-HVDC for Multiterminal Operation

PhD Candidate: Temesgen Haileselassie
Supervisors: Prof. Kjetil Uhlen, Prof. Tore Undeland

Norwegian University of Science and Tecnhology (NTNU)

Background: AC/DC Grid integration in the North Sea



Desired operational capabilities of MTDC

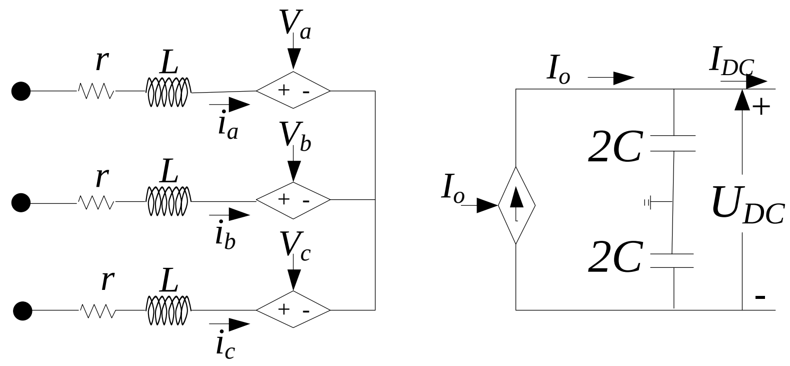
- Balancing of offshore wind power variation
- Tolerance to loss of a VSC-HVDC terminal (≈load/generation loss)
- Frequency response enhancement of AC grids
- Market integrated operation
- AC and DC fault handling capabilities

Active and Passive AC grid Connections

Passive AC grid connection:
-AC voltage control at PCC
-no synchronization
-no control of current

Active AC grid connection:
-Grid synchronization
-control of current flow

Time-average VSC model



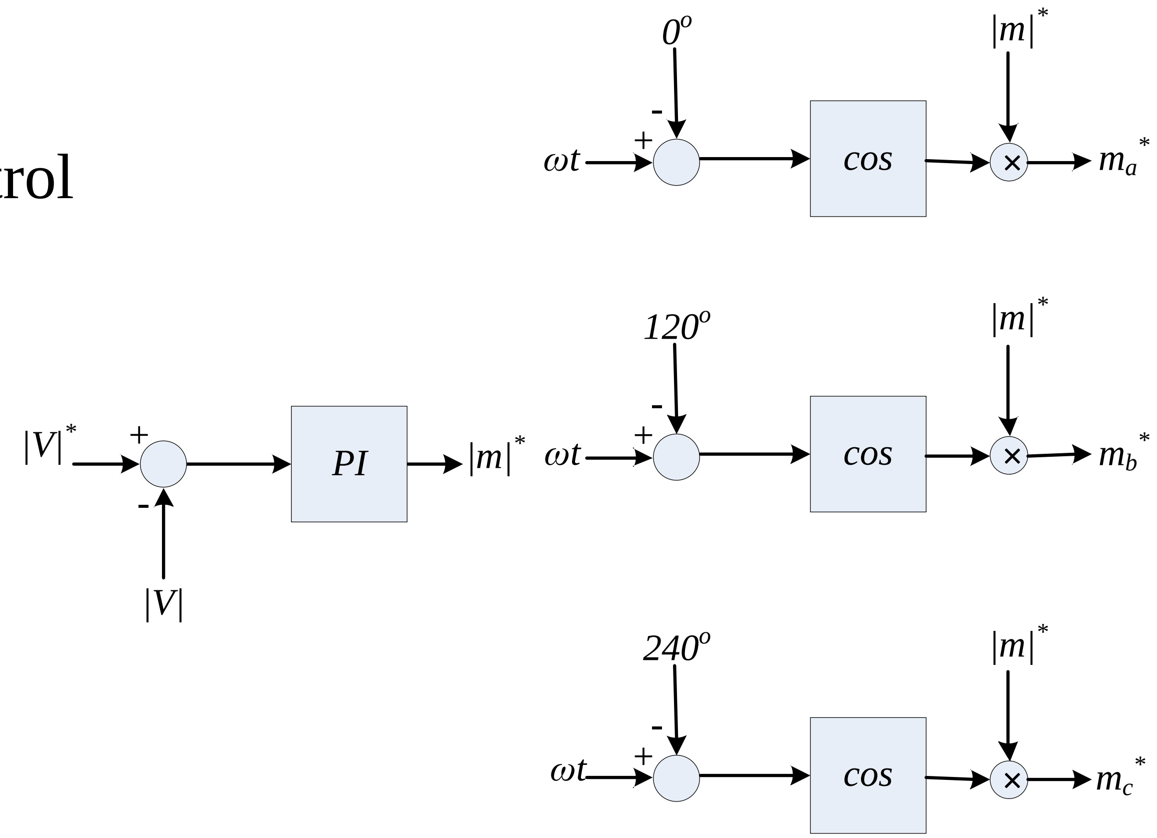
$$V_a = \frac{m_a U_{dc}}{2}, \quad V_b = \frac{m_b U_{dc}}{2}, \quad V_c = \frac{m_c U_{dc}}{2}$$

$$I_o = \frac{1}{2}\left(m_a i_a + m_b i_b + m_c i_c\right)$$

NTNU

Control of VSC Connected to Passive AC Grid

AC voltage control at PCC, |V|



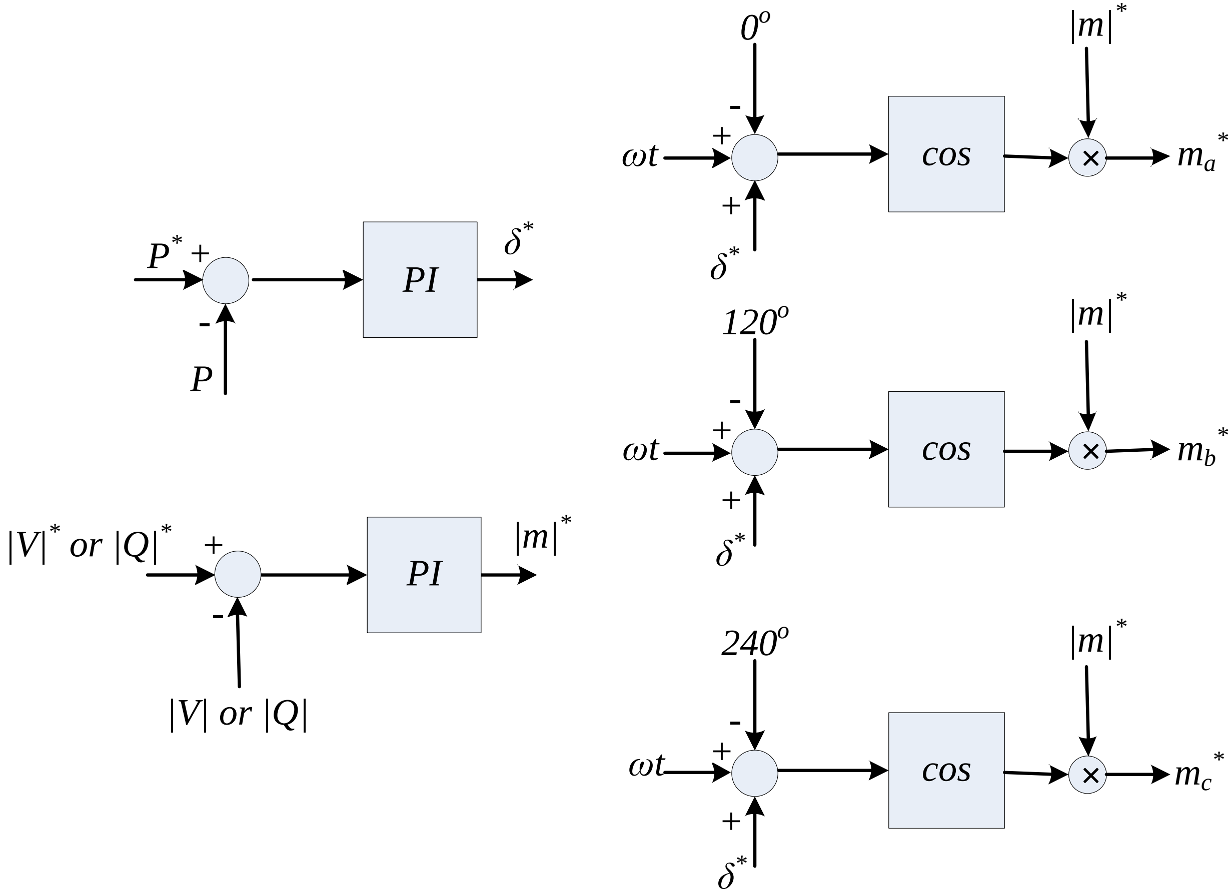
Control of VSC Connected to Active AC grid

Two options:

- ***|m|, δ control***: uses phasor measurements
- ***decoupled axes (dq) control*** : uses instantaneous measurements

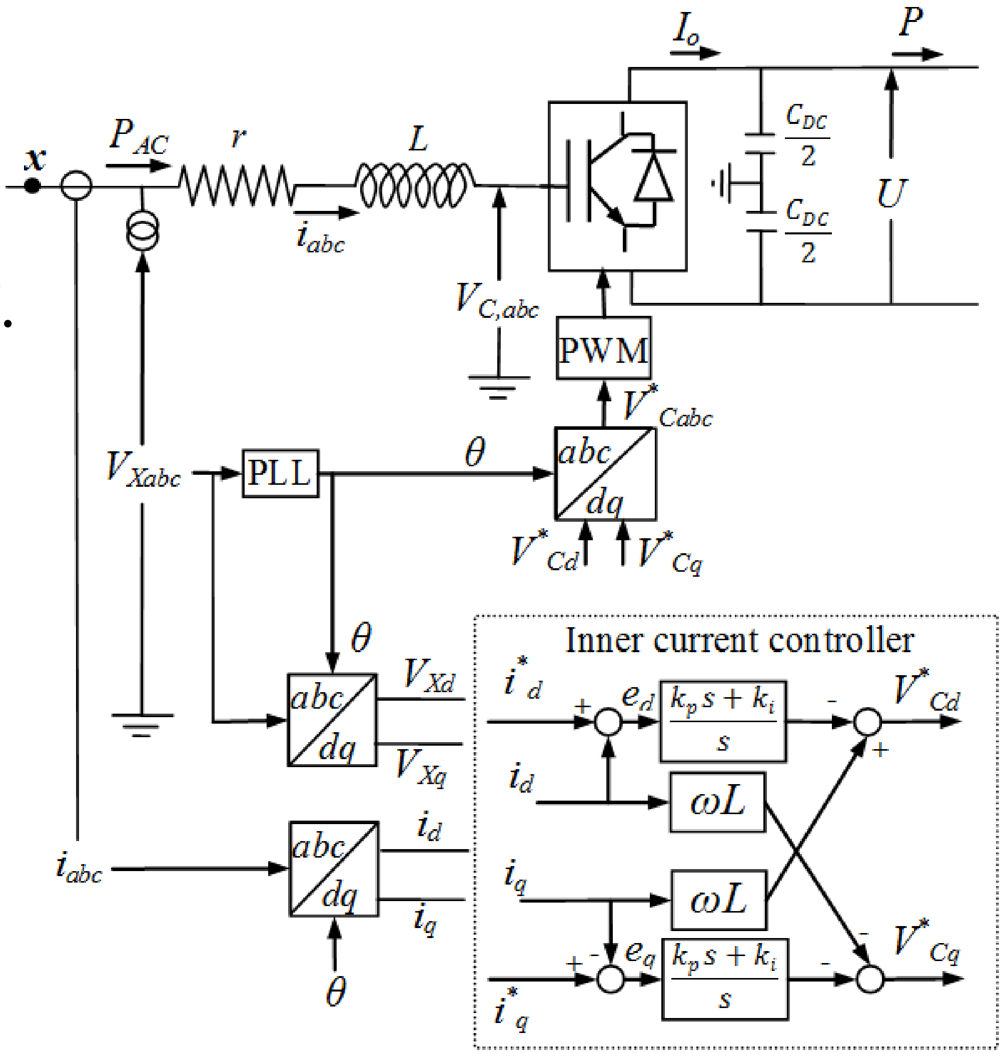
|m|, δ control

- Suitable for modelling VSC control in phasor based electric power simulation tools (eg: DIgSILENT).
- Voltage and current phasor measurements introduce additional time constant into the controllers

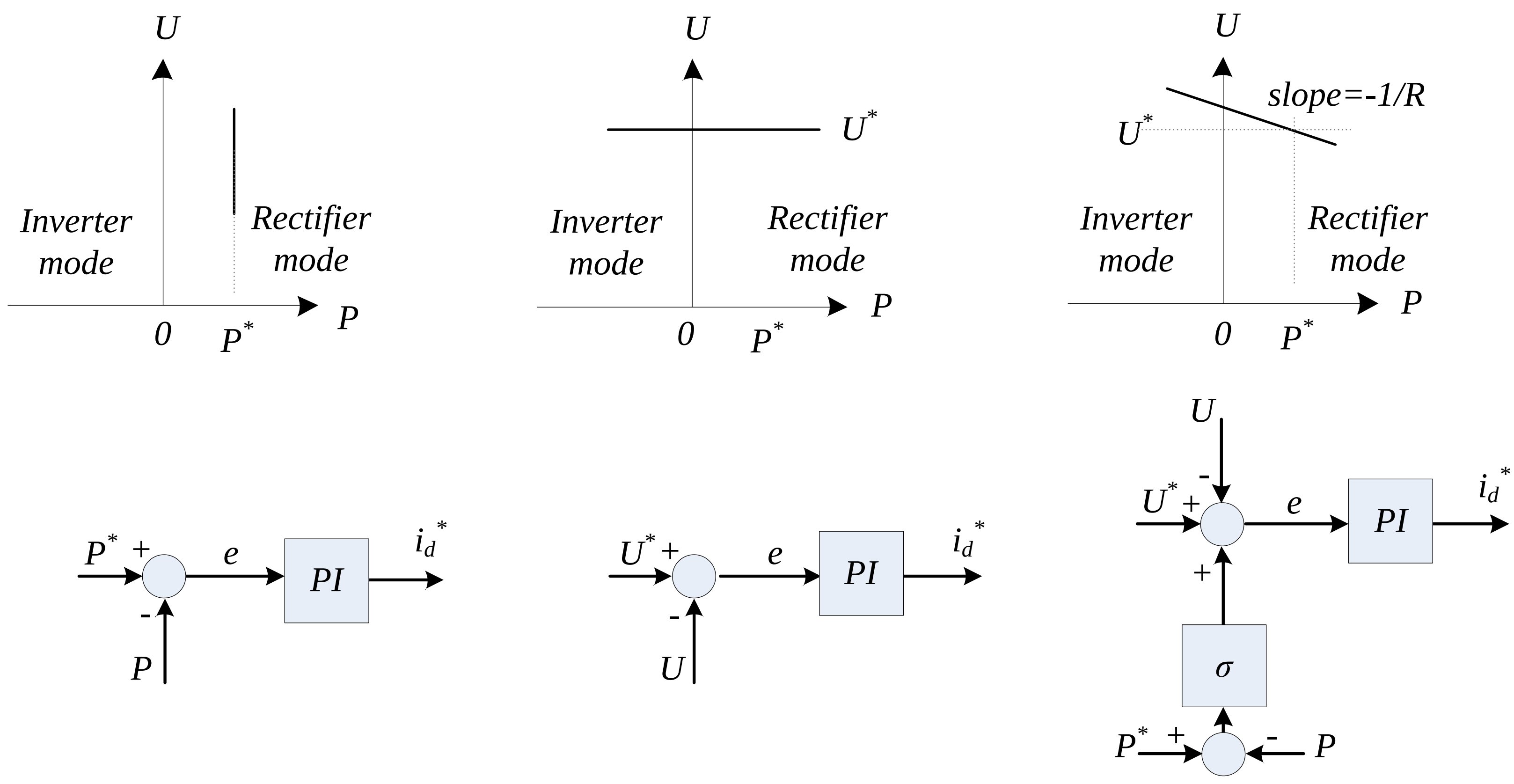


Decoupled axes (*dq*) control

- Involves abc/dq transf.
- Fast control responses
- Practically used in VSC control
- Modelling is possible with electromagnetic transient softwares such as PSCAD



Outer Controllers

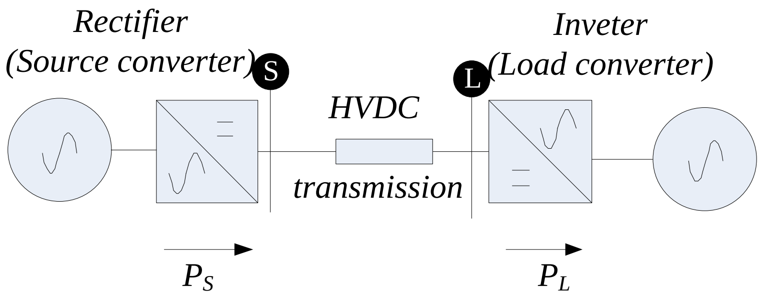


a. Fixed power control

b. Fixed DC voltage control

c. DC voltage droop controller

Two terminal VSC-HVDC Control

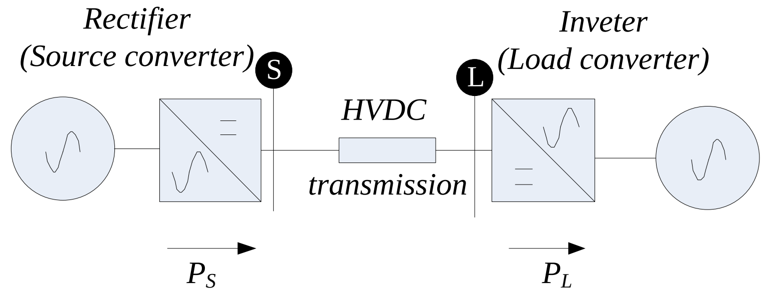


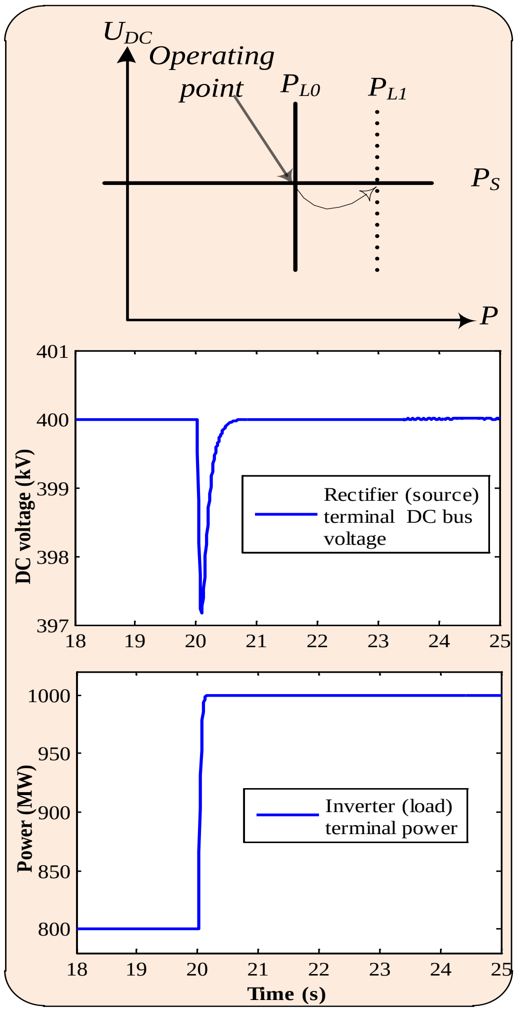
Control modes		Remarks
Rectifier	Inverter	
Fixed power	Fixed power	X (Not viable)
Fixed power	DC Droop	√ (With risk of DC overvoltage)
Fixed power	Fixed DC voltage	√ (With risk of DC overvoltage)
DC Droop	Fixed power	√ (Good, P control by Inv.)
DC Droop	DC Droop	√ (Good, P control by Both)
DC Droop	Fixed DC voltage	√ (OK, P control by Rect.)
Fixed DC voltage	Fixed power	√ (Good, P control by Inv.)
Fixed DC voltage	DC Droop	√ (Good, P control by Inv.)
Fixed DC voltage	Fixed DC voltage	X (Not viable)

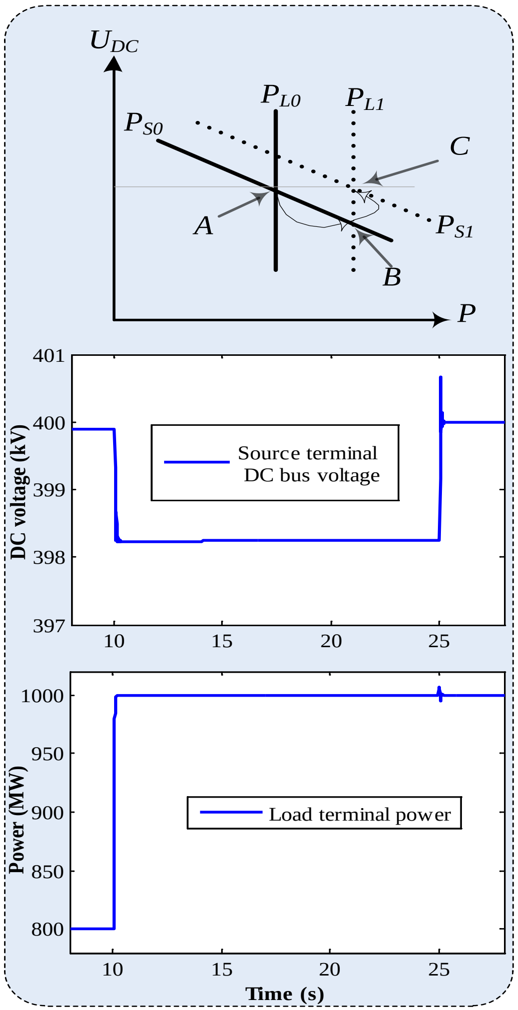
NTNU

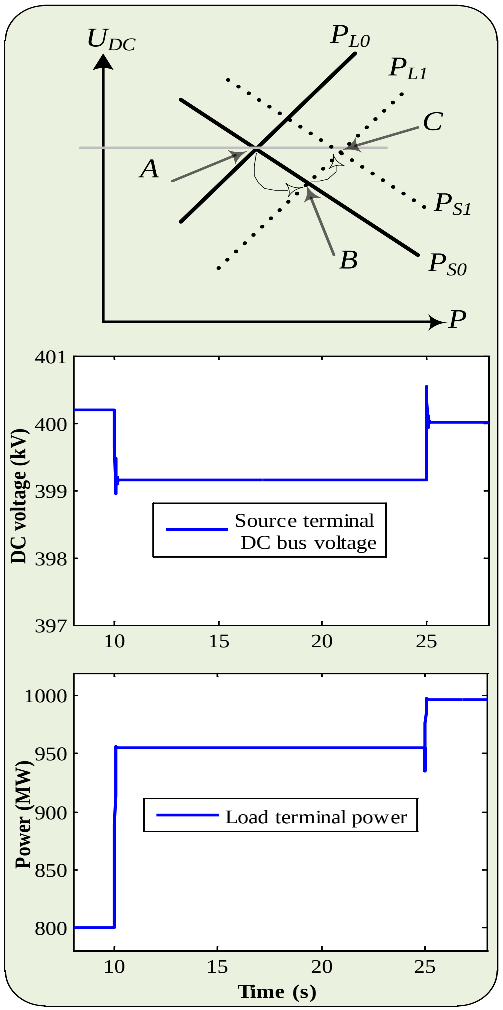
DC Voltage Control Responses

(Primary & secondary DC voltage control)



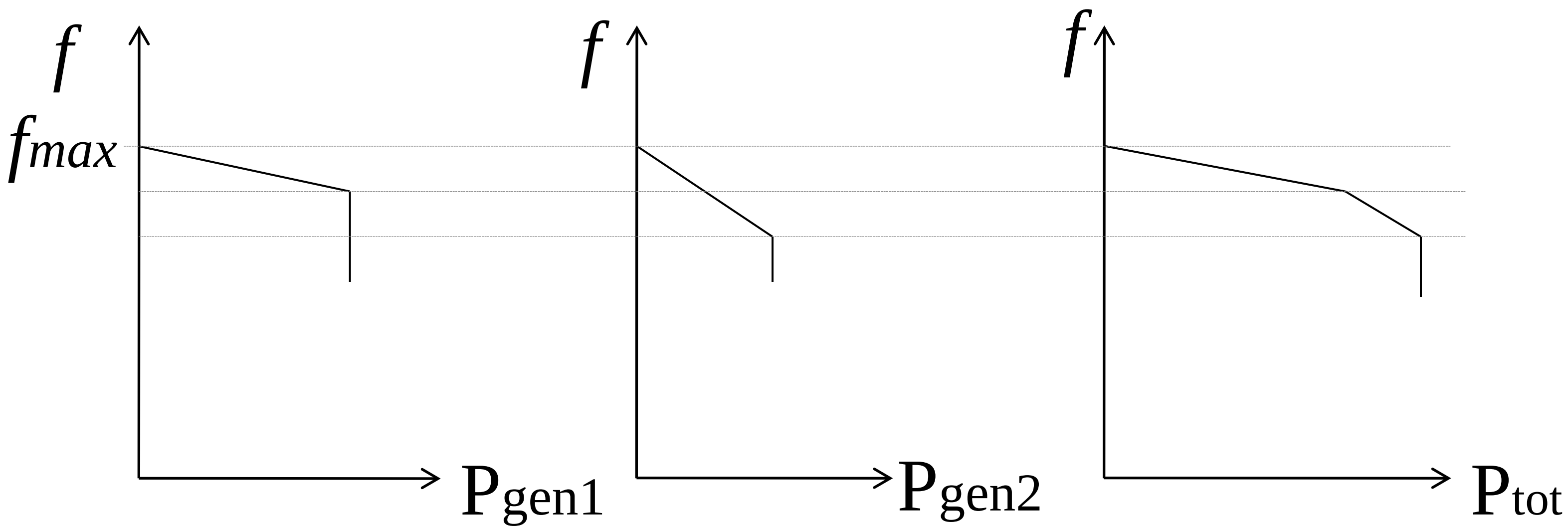






Power balance control in AC grids:

Traditionally by frequency droop (Primary frequency control)

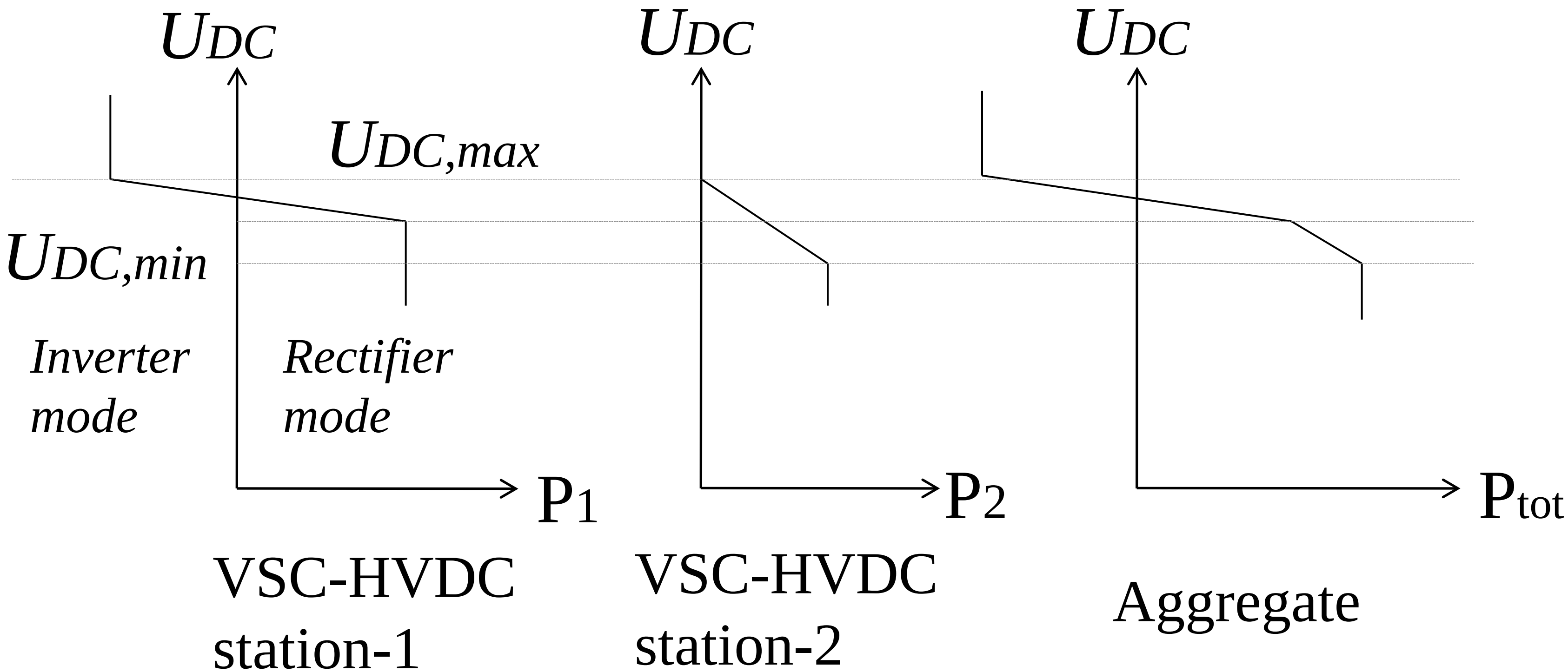


Generation station-1

Generation station-2

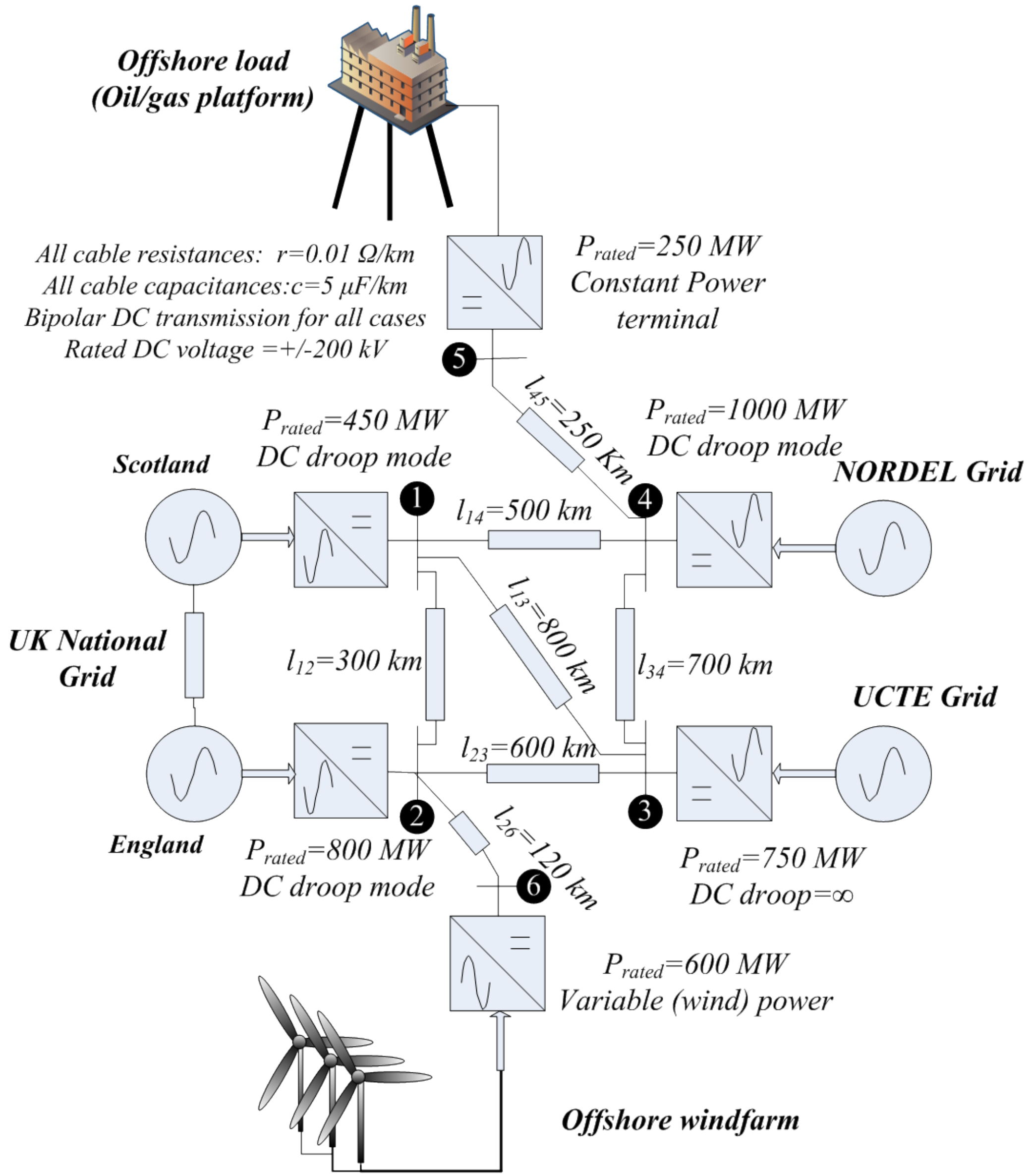
Aggregate

Power flow control in DC grid : achieved by DC voltage droop

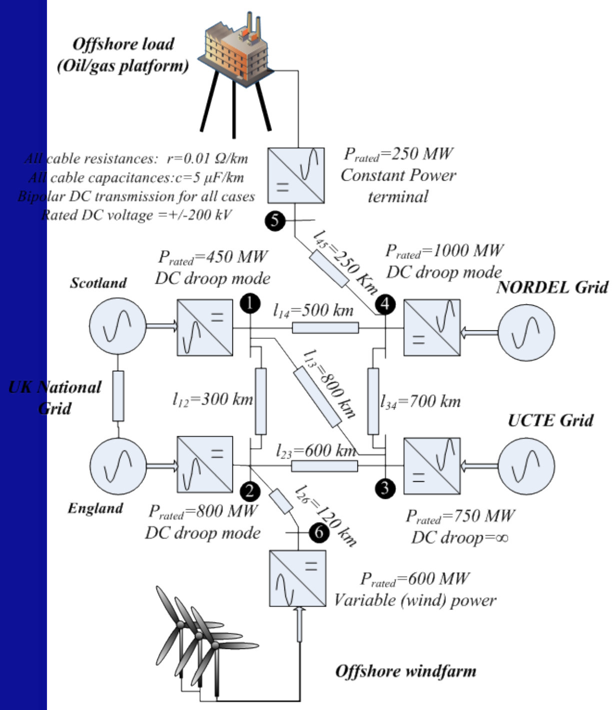


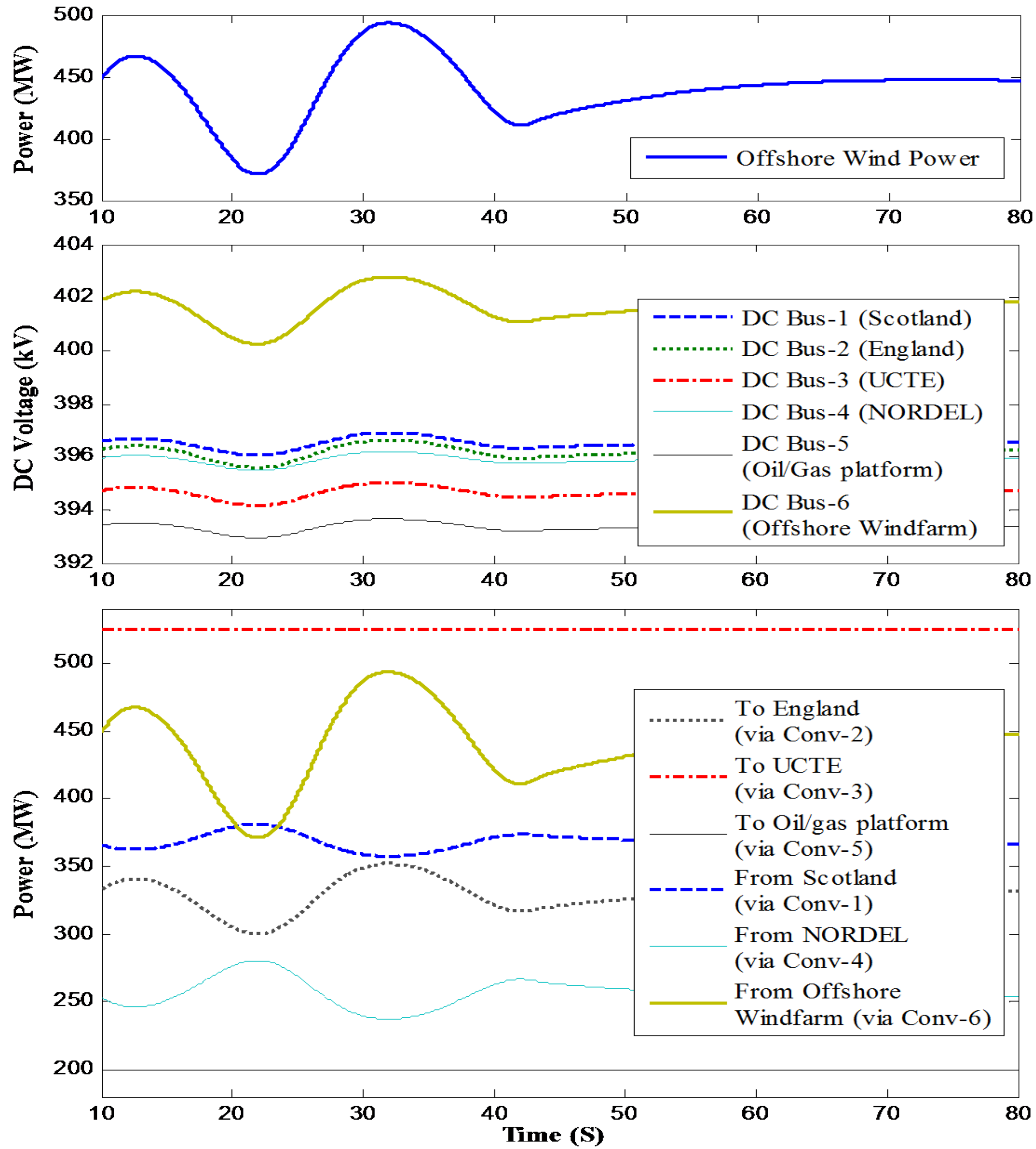
- **No need for communication between terminals**
- **Many converter terminals contribute to dc voltage regulation**
- **DC analogy to distributed *frequency droop control* in AC systems**

North Sea DC grid: A test model



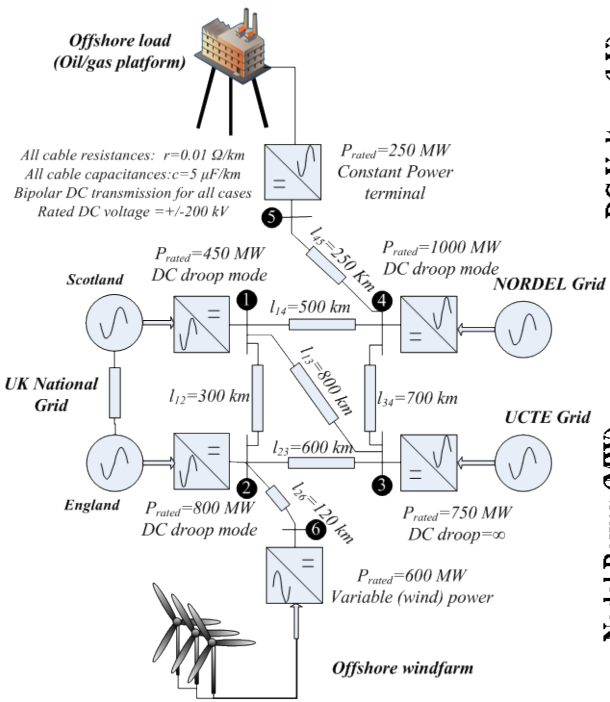
Variations of DC voltage with fluctuating wind power and DC droop control responses

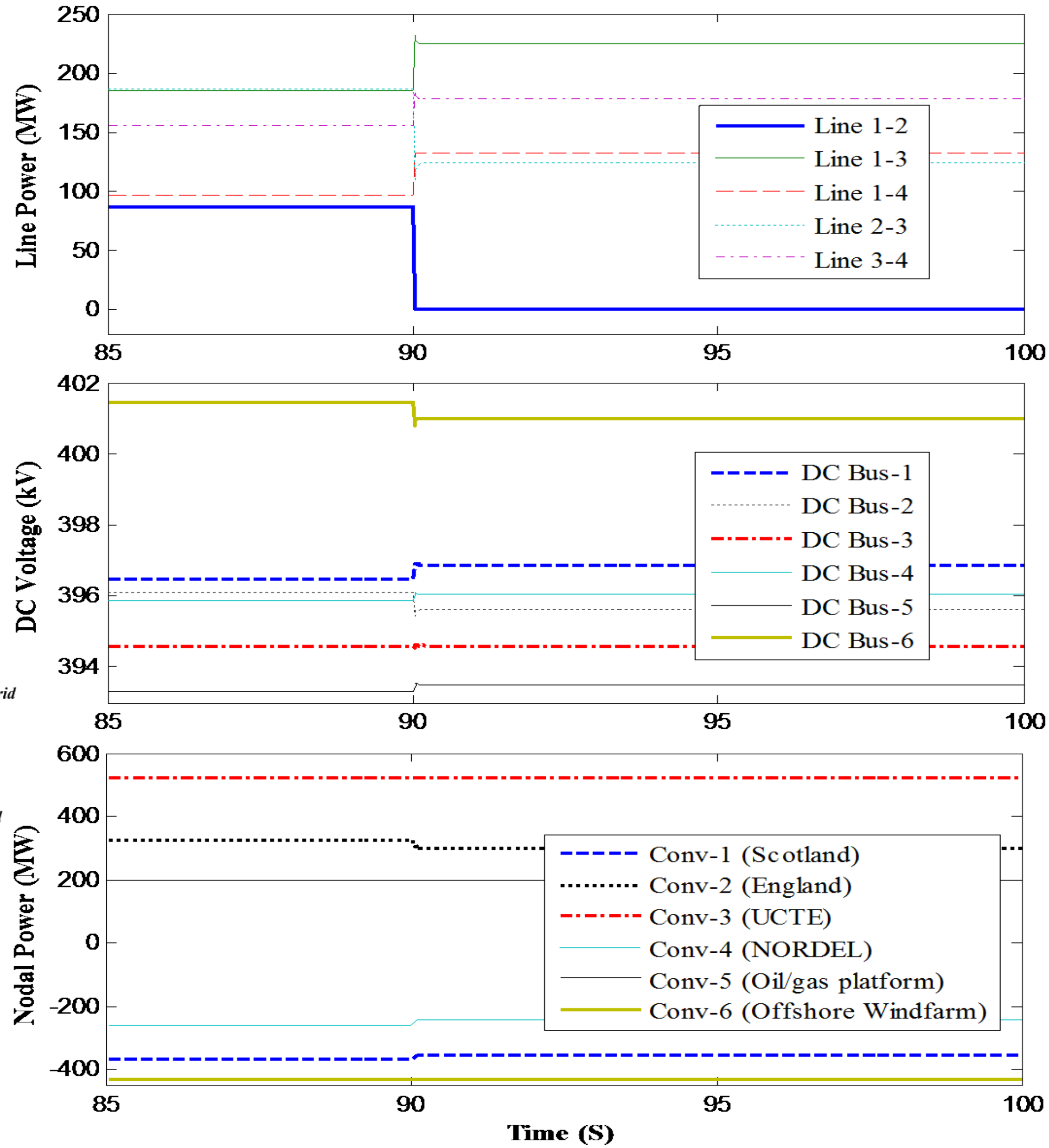




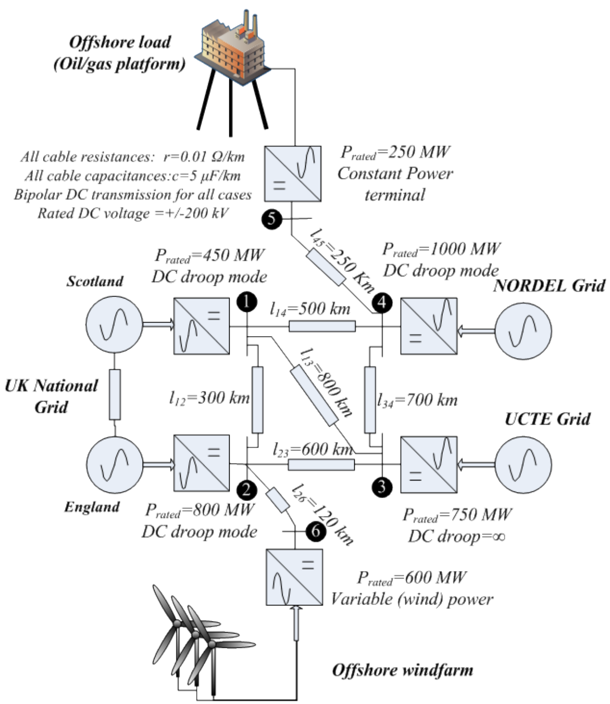
Outage of DC line 1-2

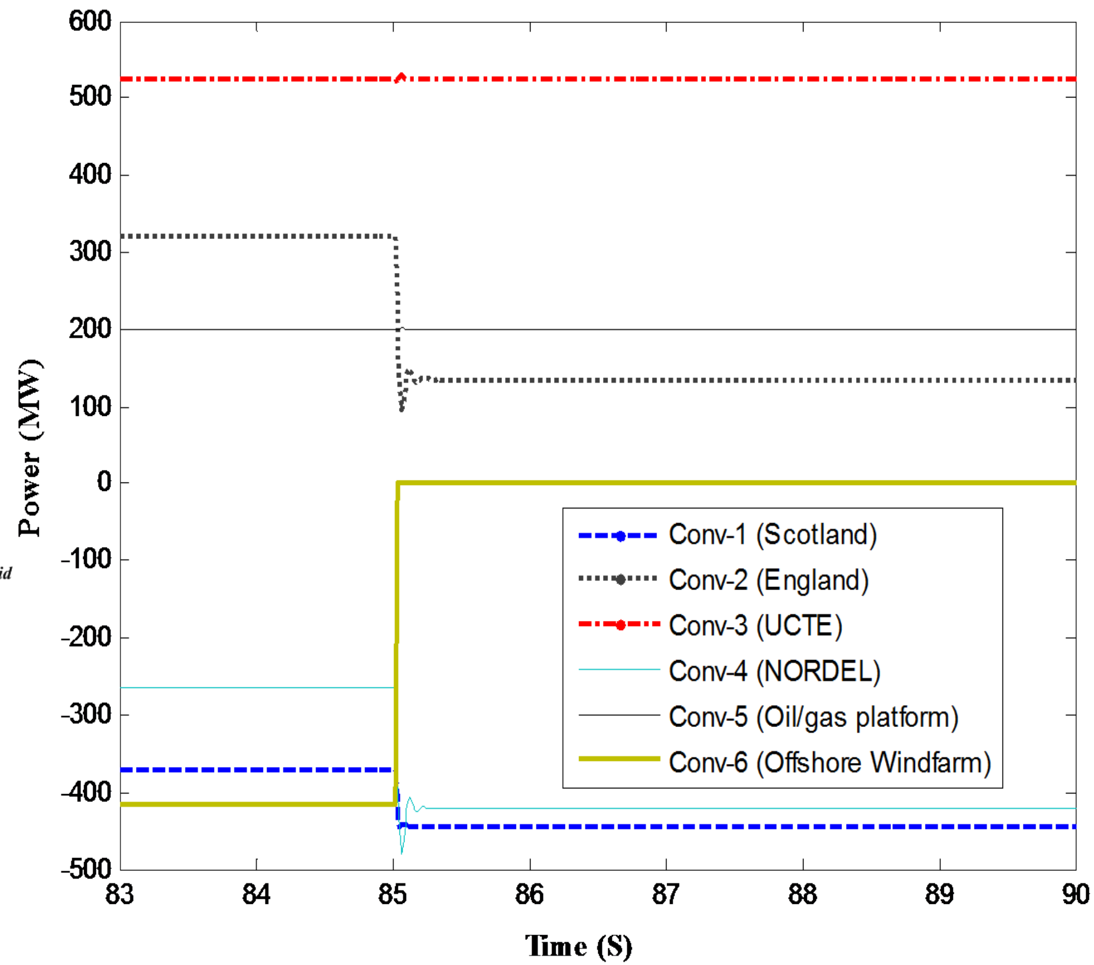
Terminal-1 (Conv-1) continues to draw power from DC grid via lines 1-3 and 1-4 when line 1-2 is disconnected.





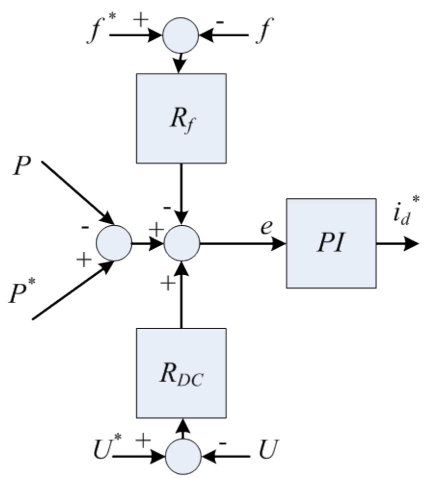
Outage of connection to windfarm

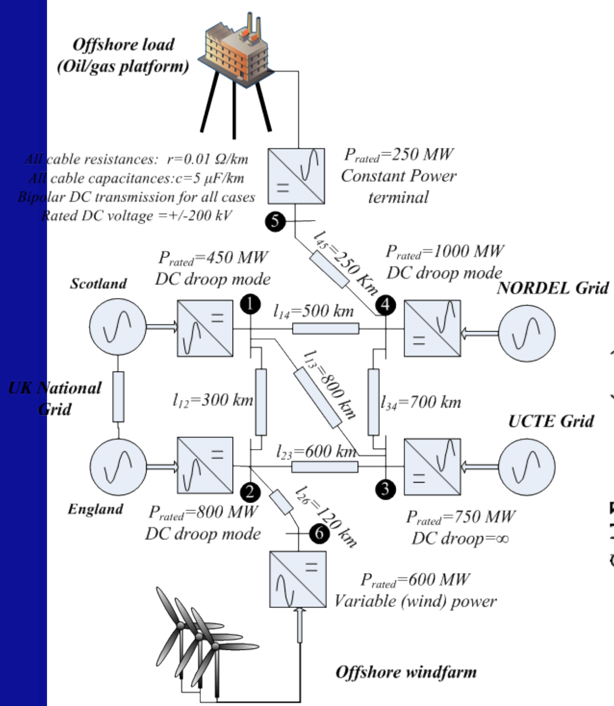


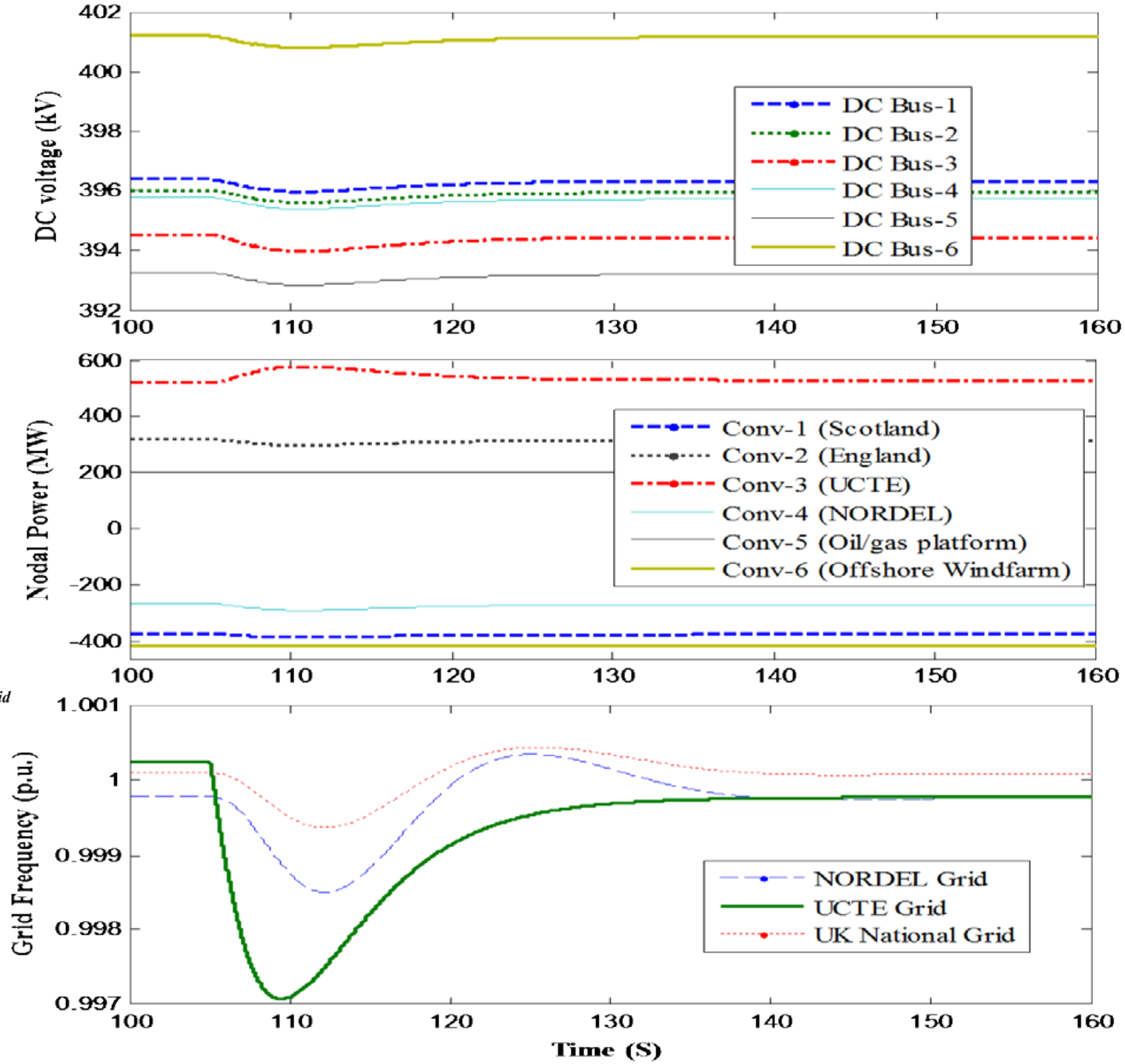


Terminals 1, 2 and 4 compensate for lost power flow from offshore wind farm.

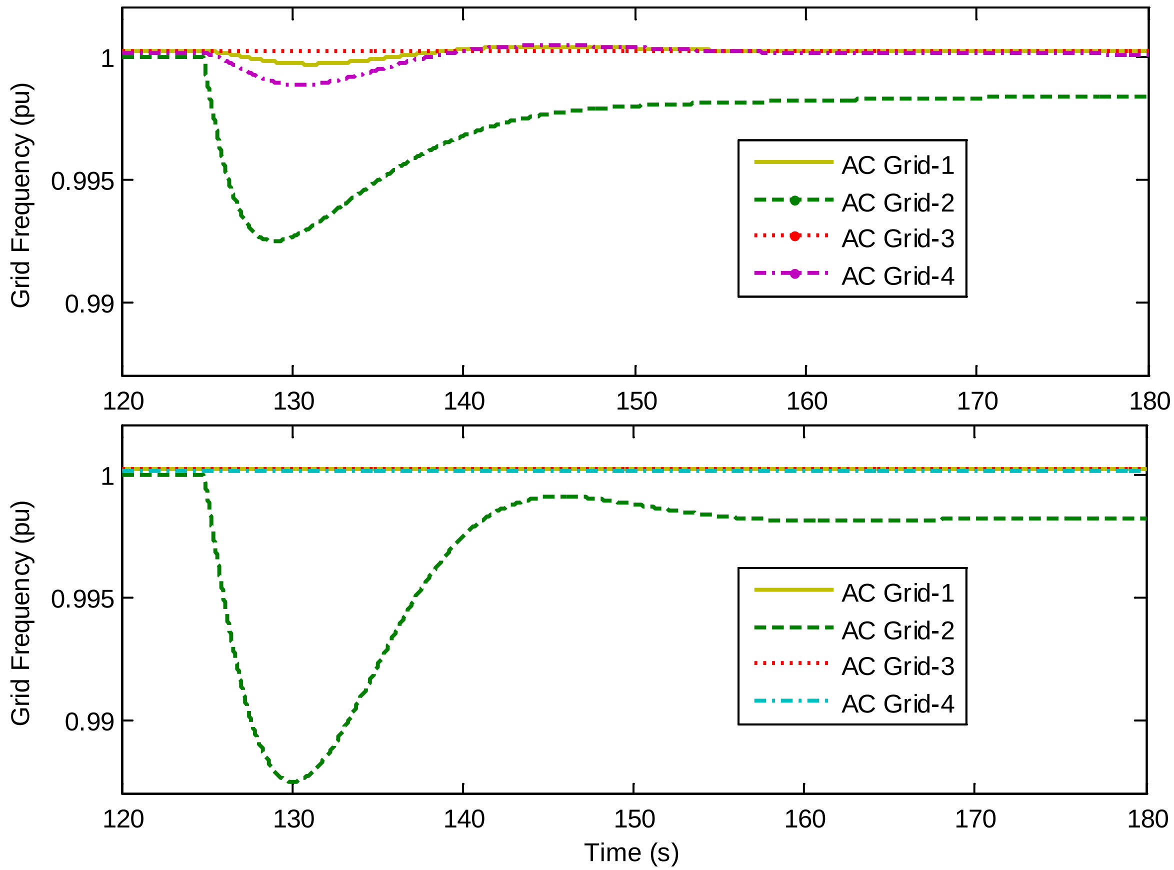
Frequency response enhancement of AC grids by MTDC







Comparison of grid responses: with and without frequency support from DC grid

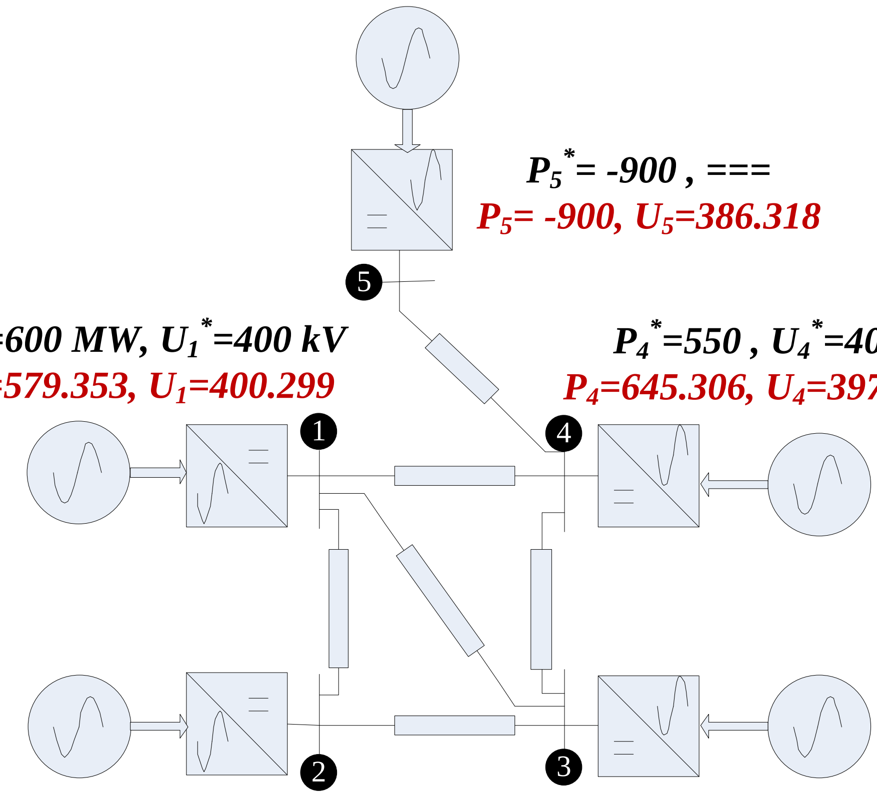


Frequency response improves with presence of frequency support from DC grid.

Precise control of power flow

Schedule/ dispatch			Control type
Terminal No.	P_{DC} (MW)	U_{DC} (kV)	
1	600	-	Droop
2	-	400	Droop
3	-750	-	Fixed P
4	550	-	Droop
5	-900	-	Fixed P

Control references			Control type
Terminal No.	P_{DC} (MW)	U_{DC} (kV)	
1	600	400	Droop
2	500	400	Droop
3	-750	400	Fixed P
4	550	400	Droop
5	-900	400	Fixed P



$P_5^* = -900$, ===
$P_5 = -900, U_5 = 386.318$

$P_1^* = 600$ MW, $U_1^* = 400$ kV
$P_1 = 579.353, U_1 = 400.299$

$P_4^* = 550$, $U_4^* = 400$
$P_4 = 645.306, U_4 = 397.967$

$P_2^* = 500$, $U_2^* = 400$
$P_2 = 459.775, U_2 = 400.503$

$P_3^* = -750$, ===
$P_3 = -750, U_3 = 397.376$

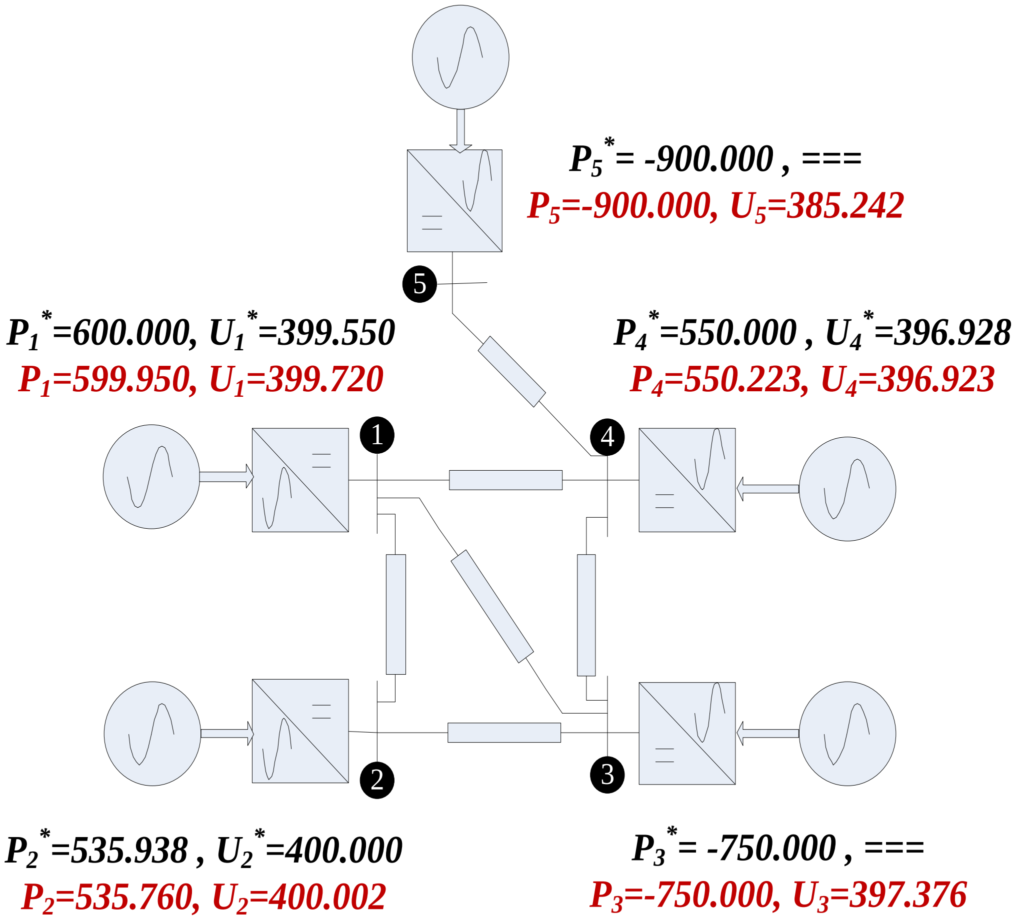
Not precise!

Cntd…

Schedule/ dispatch			Control type
Terminal No.	P_{DC} (MW)	U_{DC} (kV)	
1	600	-	Droop
2	-	400	Droop
3	-750	-	Fixed P
4	550	-	Droop
5	-900	-	Fixed P

DC Power flow analyisis

Control references			Control type
Terminal No.	P_{DC} (MW)	U_{DC} (kV)	
1	600.00	399.550	Droop
2	535.94	400.000	Droop
3	-750.00	396.613	Fixed P
4	550.00	396.928	Droop
5	-900.00	385.247	Fixed P

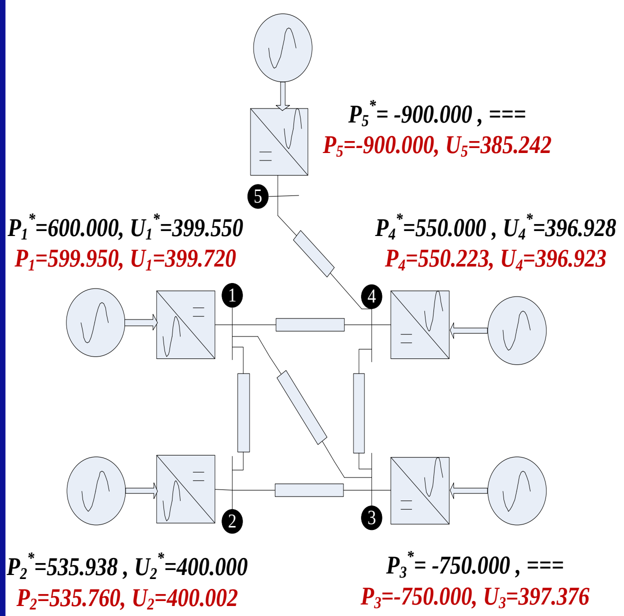


Precise!

(Desired power flow achieved)

Impact of DC Resistance on DC grid Balancing Power Distribution

-A step change of $\Delta P_3^* = -50$ MW applied to terminal-3
-Unequal compensations, ΔP_{DC} (pu), by terminals-1, 2, 4 & 5 observed



Terminal No.	1	2	3	4	5
U_{DC} (kV)	399.287	399.726	396.204	396.677	385.118
P_{DC} (MW)	618.293	552.483	-800.000	565.853	-900.028
ΔU_{DC} (kV)	-0.263	-0.274	-0.409	-0.251	-0.129
ΔP_{DC} (MW)	**14.820**	**13.723**	**-50.000**	**11.741**	**9.67**
P_{Rated}(MW)	900	800	1000	750	1200
ΔP_{DC} (pu)	**0.01647**	**0.01715**	-0.05	**0.01565**	**0.00806**

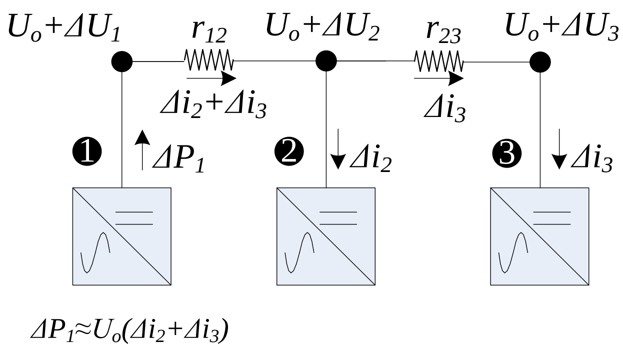
Small signal equivalent circuit for studying balancing power distribution

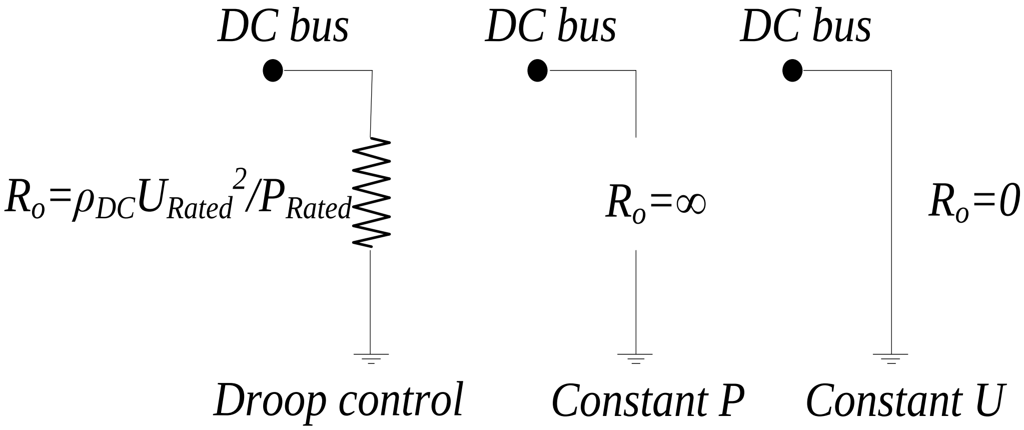
Dynamic output resistance of a VSC station

$$R_{o-i} = \frac{\Delta U_{DC-i}}{\Delta I_{DC-i}} = \frac{\Delta U_{DC-i}}{\Delta P_{DC-i} / U_{DC-i}}$$

$$= U_{DC} \frac{U_{Rated-i}}{P_{Rated-i}} \left(\frac{\Delta U_{DC-i} / U_{rated}}{\Delta P_{DC-i} / P_{rated}} \right)$$

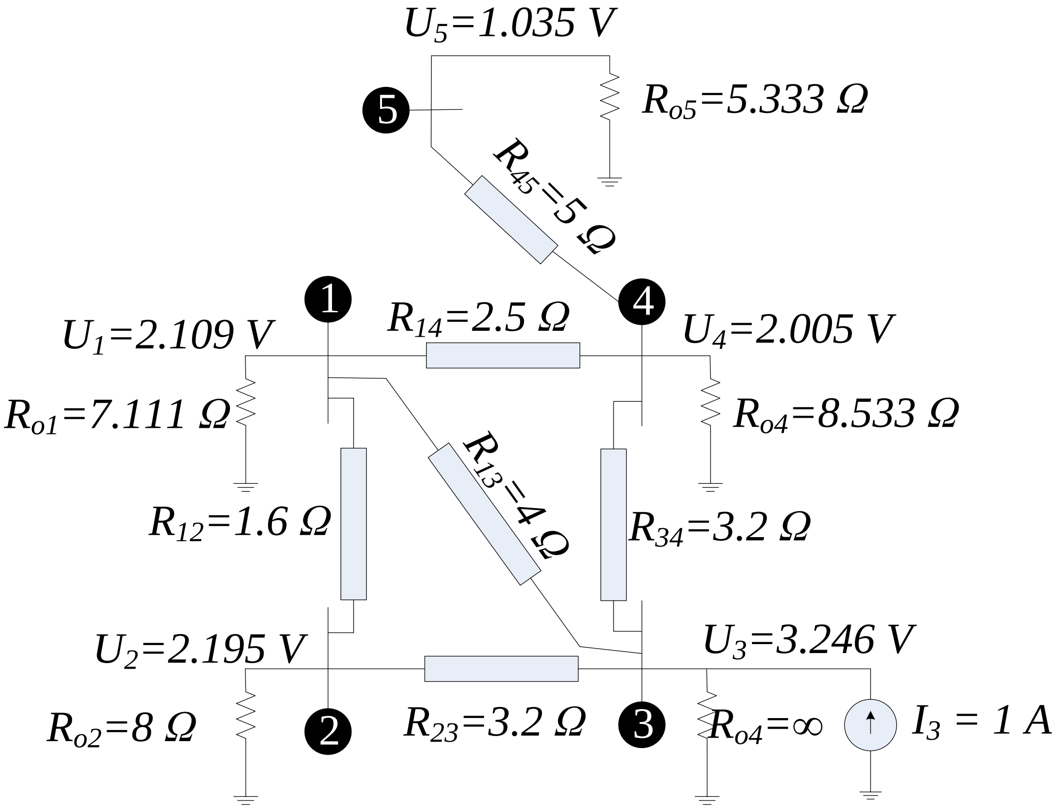
$$\approx \rho_{DC-i} \frac{U^2_{Rated-i}}{P_{Rated-i}}$$





Example: Small signal circuit for the five terminal VSC-HVDC

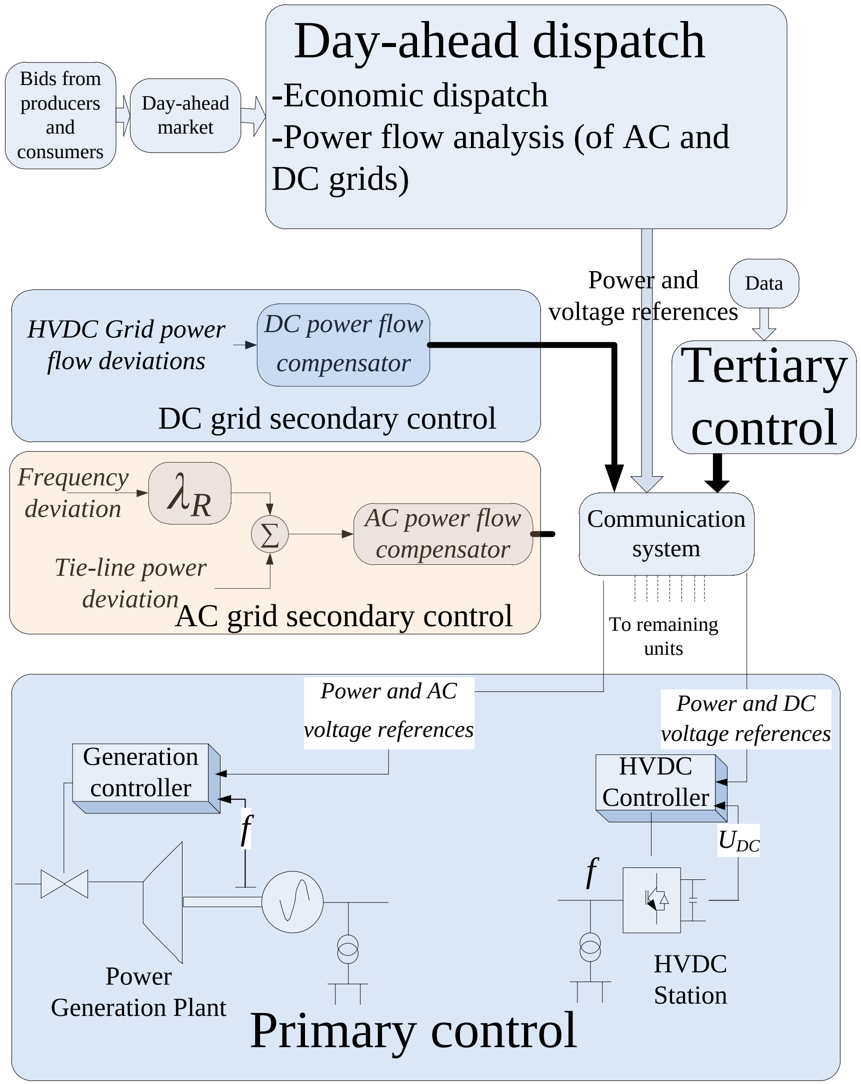
Impedances (Ω)	Changes due to ΔP_{DC-3}^{ref}=-50 MW	
	ΔU_{DC} (kV)	ΔP_{DC} (pu)
Z_{33}=3.246	-0.409	-0.05
Z_{32}=2.195	-0.274	0.01715
Z_{31}=2.109	-0.263	0.01647
Z_{34}=2.005	-0.251	0.01565
Z_{35}=1.035	-0.129	0.00806

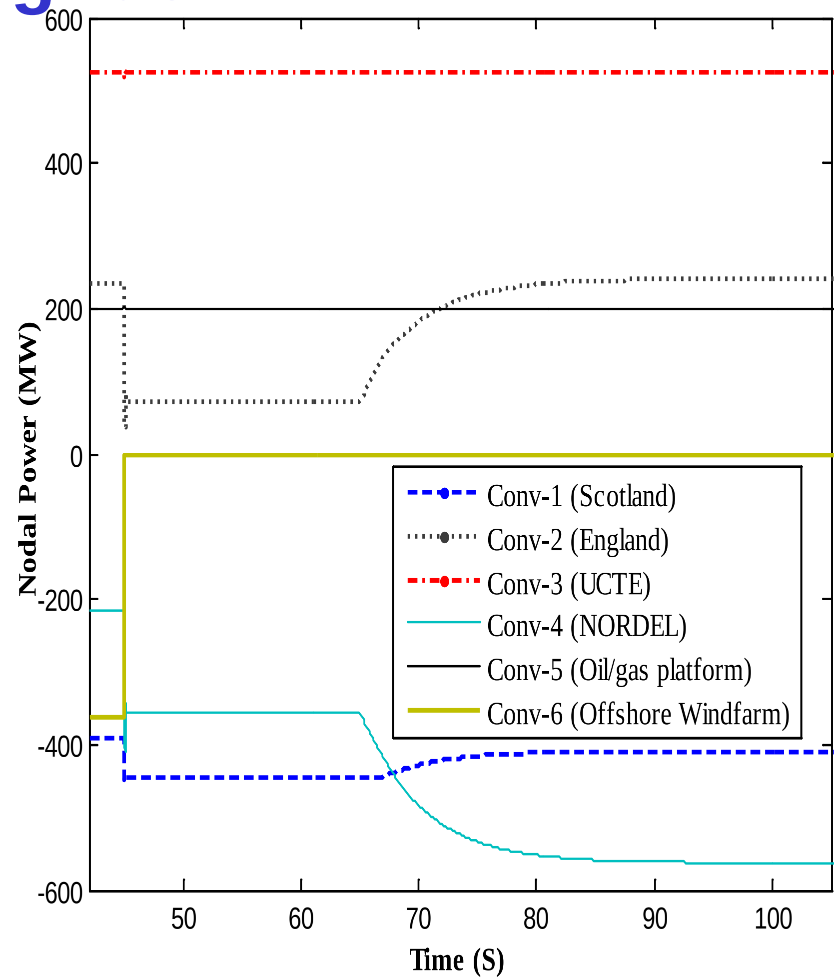


Strong droop response for power flow change occuring at closer electrical distance

$$R_{o-i} = \frac{\Delta U_{DC-i}}{\Delta I_{DC-i}} \approx \rho_{DC-i} \frac{U_{Rated-i}^2}{P_{Rated-i}}$$

Primary, secondary and tertiary controls of AC/DC grids





Secondary control response of HVDC grid for loss of connection to offshore wind farm

Thank you!