Control and Operation of Multi-terminal VSC-HVDC

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Conclusions / Hypothesis

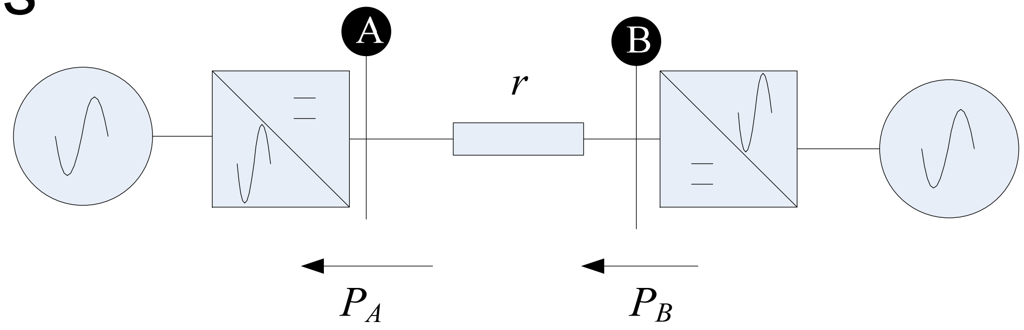
- ***A meshed HVDC grid has the potential to improve security of supply!***
- A multi-terminal HVDC grid in the North Sea can effectively integrate the synchronous interconnections (UK, UCTE and Nordic)
- Can be operated as ONE control area (if desirable)
- Reserves (primary and secondary) can be shared without "technical constraints"
- Fast control and protection will enable network splitting to avoid risk of cascading outages and complete blackouts
- Fully integrate the power markets across the asynchronous areas.

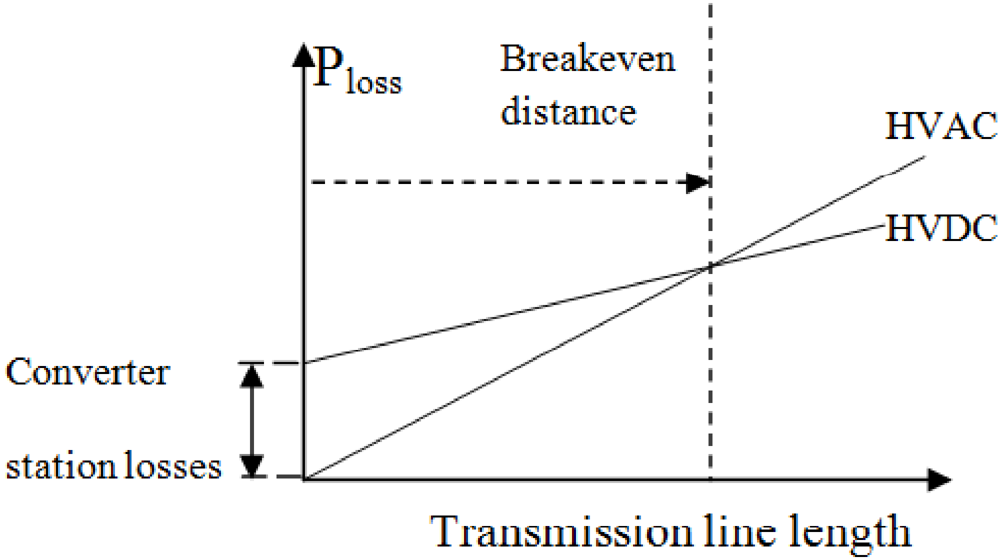
Outline

- Introduction: Why HVDC – VSC HVDC – Multi-terminal HVDC
- Power system security and Control objectives
- Modelling and control design
- Examples (illustrating security control aspects)

HVDC Why?

1. To reduce total transmission loss for long distance power lines



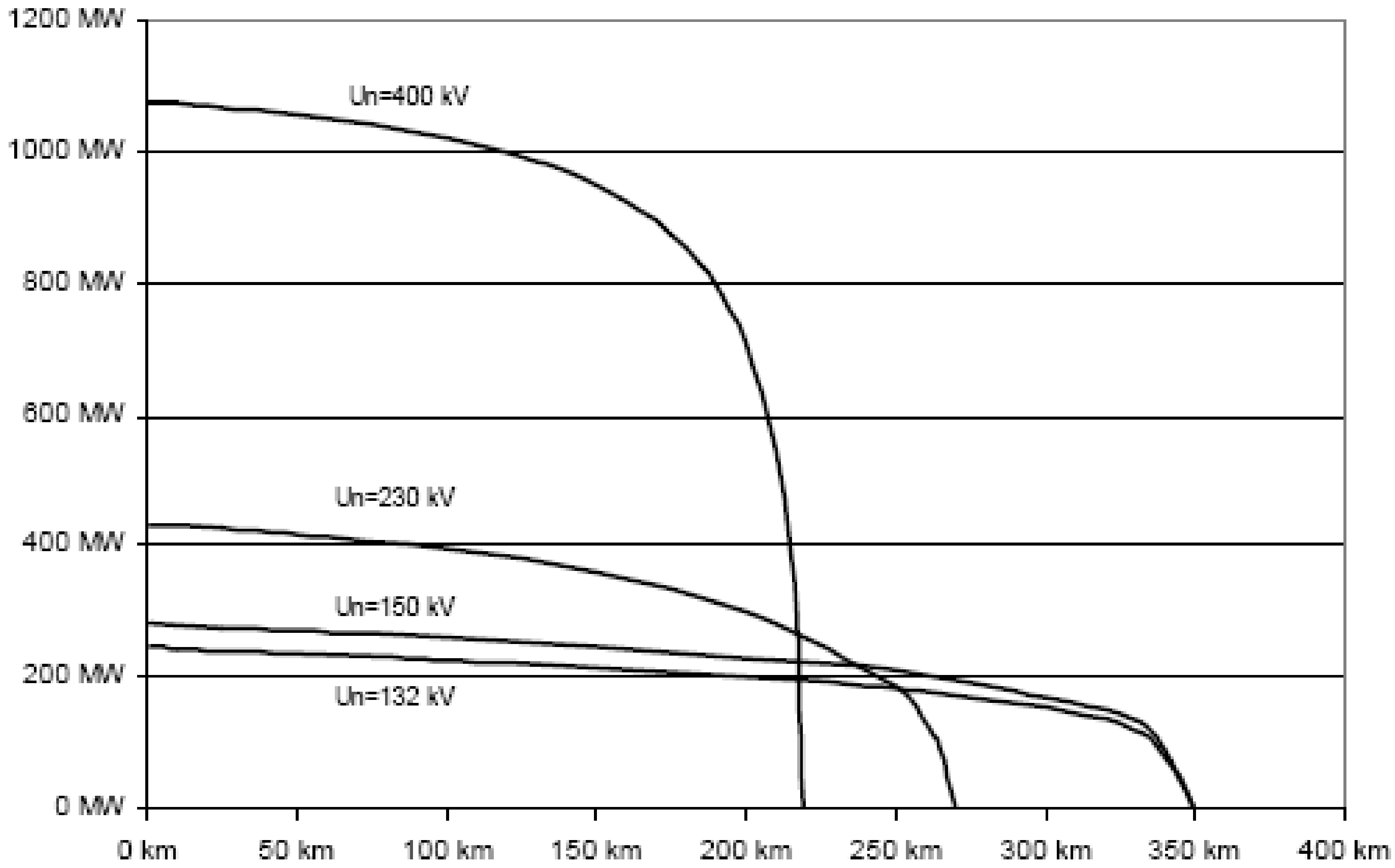


Break even distance for onshore application is about 600km and less than 100km for subsea transmissions

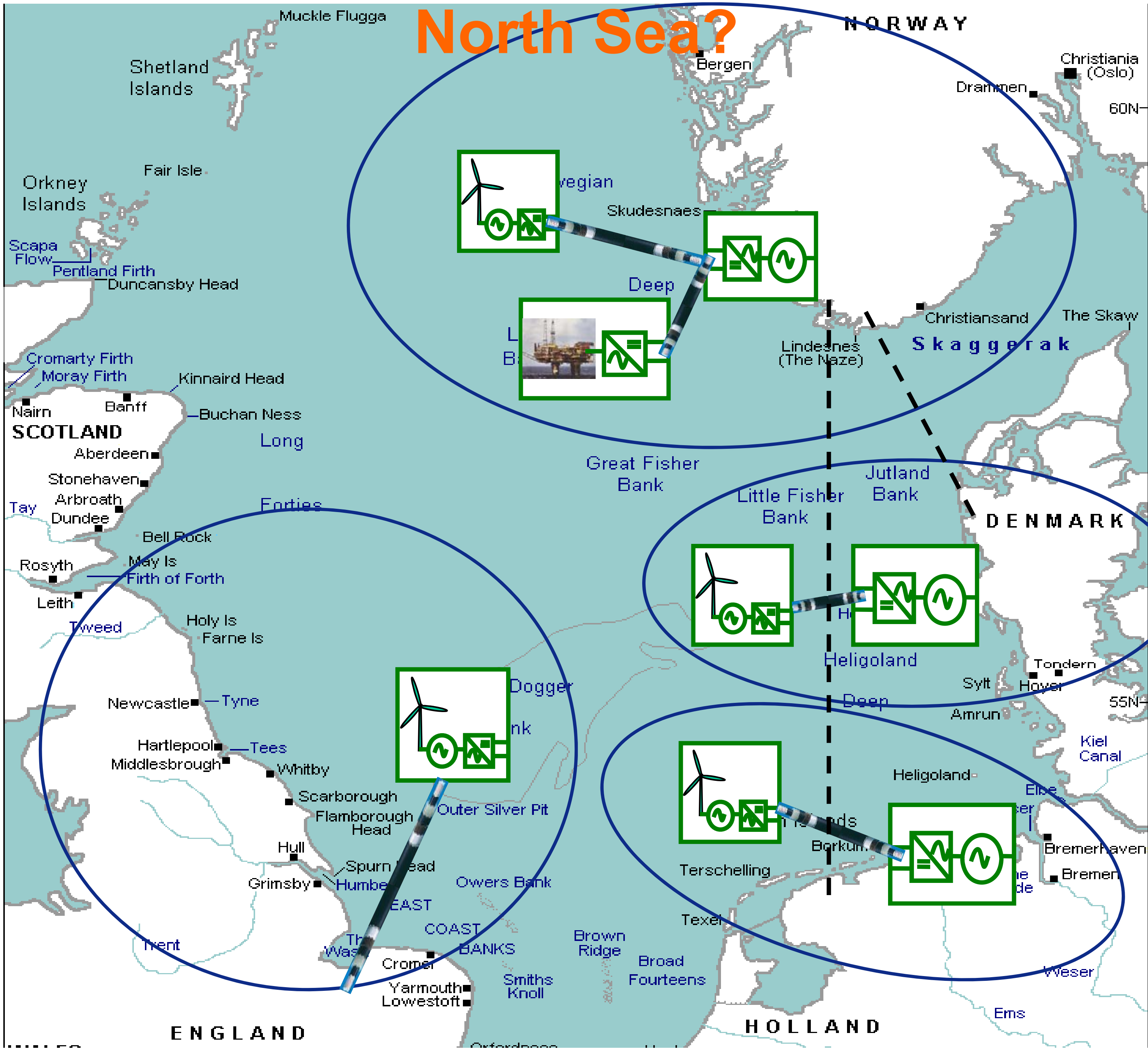
Cont…

2. AC transmission becomes weak (unstable) for very large distances
3. Subsea power transmission
   - Large capacitive currents in AC cables severly limit the transmission capacity of long distance AC cables
   - The most common application area of HVDC is for subsea power transmission

Limits of transmission capacity, Submarine HVAC cables (ref Nexans)



Why multiterminal VSC-HVDC (MTDC) in the North Sea?



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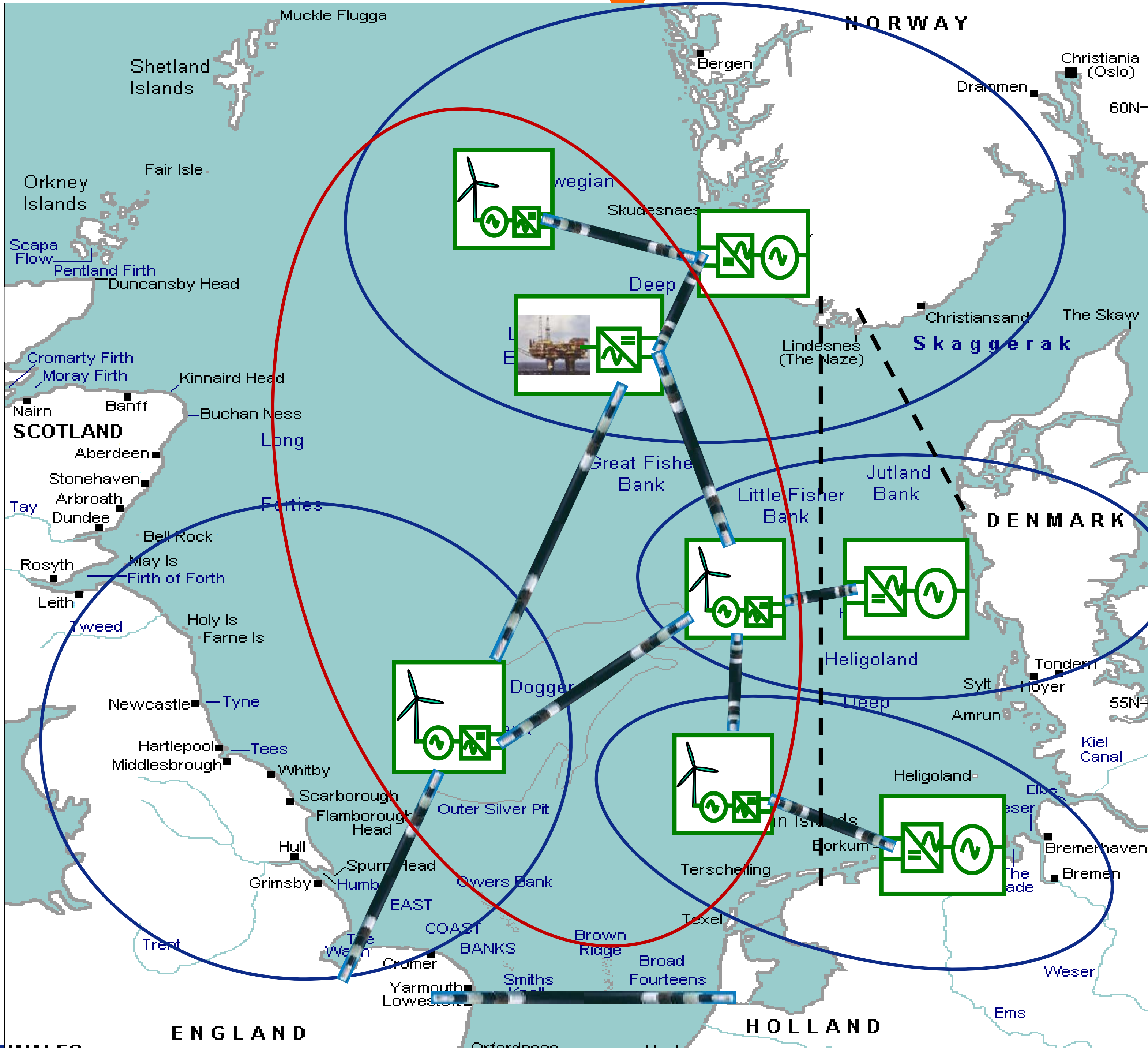
Grid integration



Power system security

- Security standards: Deterministic (N-1) or risk based

- Ability to manage contingencies / outages:
  - Availability of reserves
  - Availability of transmission capacity
  - Stability and control

Main challenges in operation and control

- Primary control:
  - Less primary reserves if new generation provide less frequency response
- Secondary control:
  - More need for secondary reserves with more variable generation
- Tertiary control:
  - Benefits with larger control areas and exchange of reserves.

- **New possibilities with an offshore Multi-terminal HVDC grid!**

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Control objectives: Desired operational capabilities

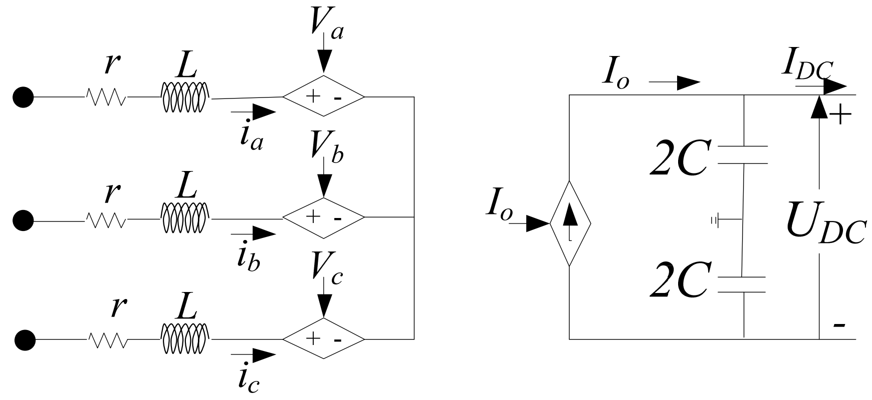
- Balancing of offshore wind power variation
- Resilience, e.g. to loss of a VSC-HVDC terminal (≈load/generation loss) or line/cable
- Frequency response enhancement of AC grids
- Market integrated operation
- AC and DC fault handling capabilities

Controllers should be designed to meet the requirements specified above.

Modelling:
Active and Passive AC grid Connections

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

Time-average VSC model



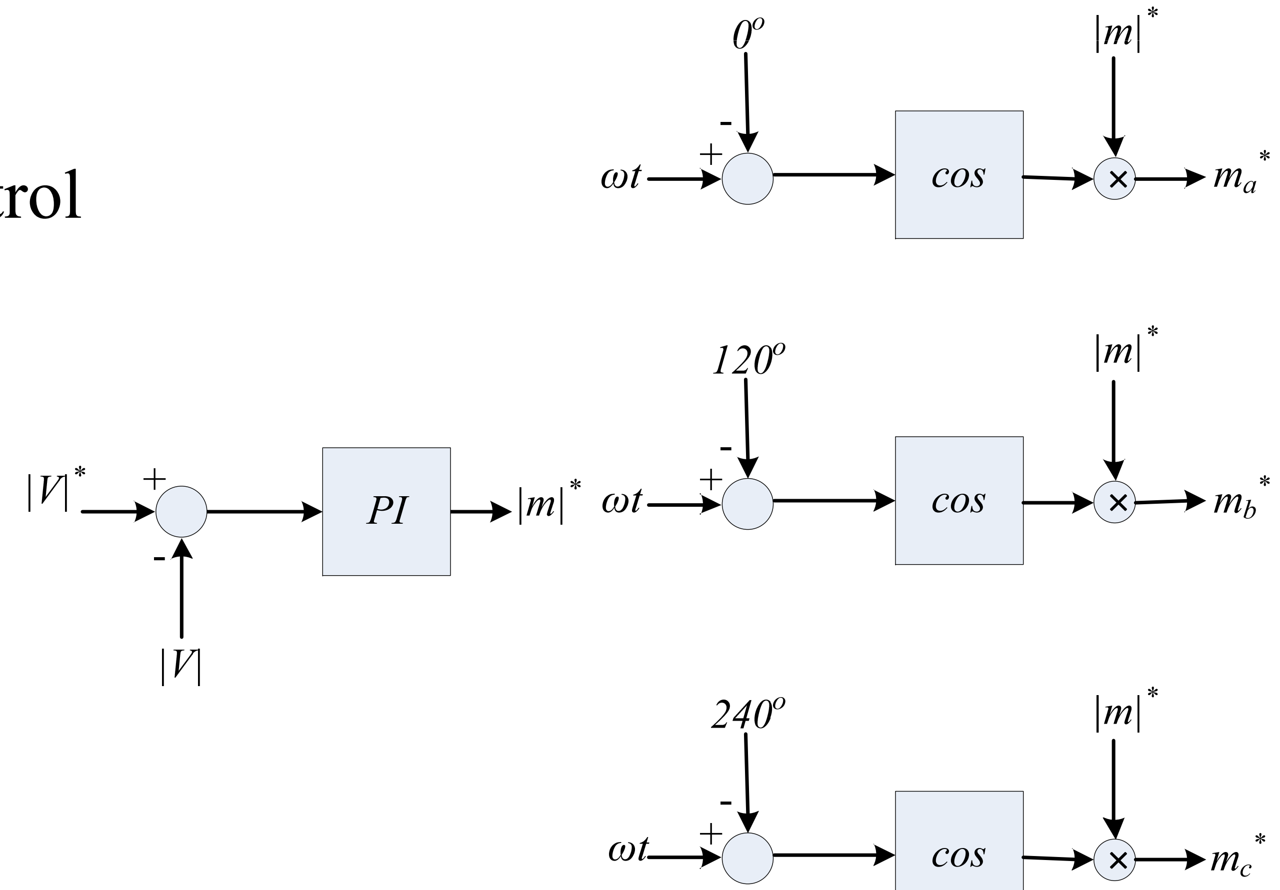
$$V_a = \frac{m_a U_{dc}}{2}, \quad V_b = \frac{m_b U_{dc}}{2}, \quad V_c = \frac{m_c U_{dc}}{2}$$

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

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

Control of VSC Connected to Passive AC Grid

AC voltage control at PCC, |V|



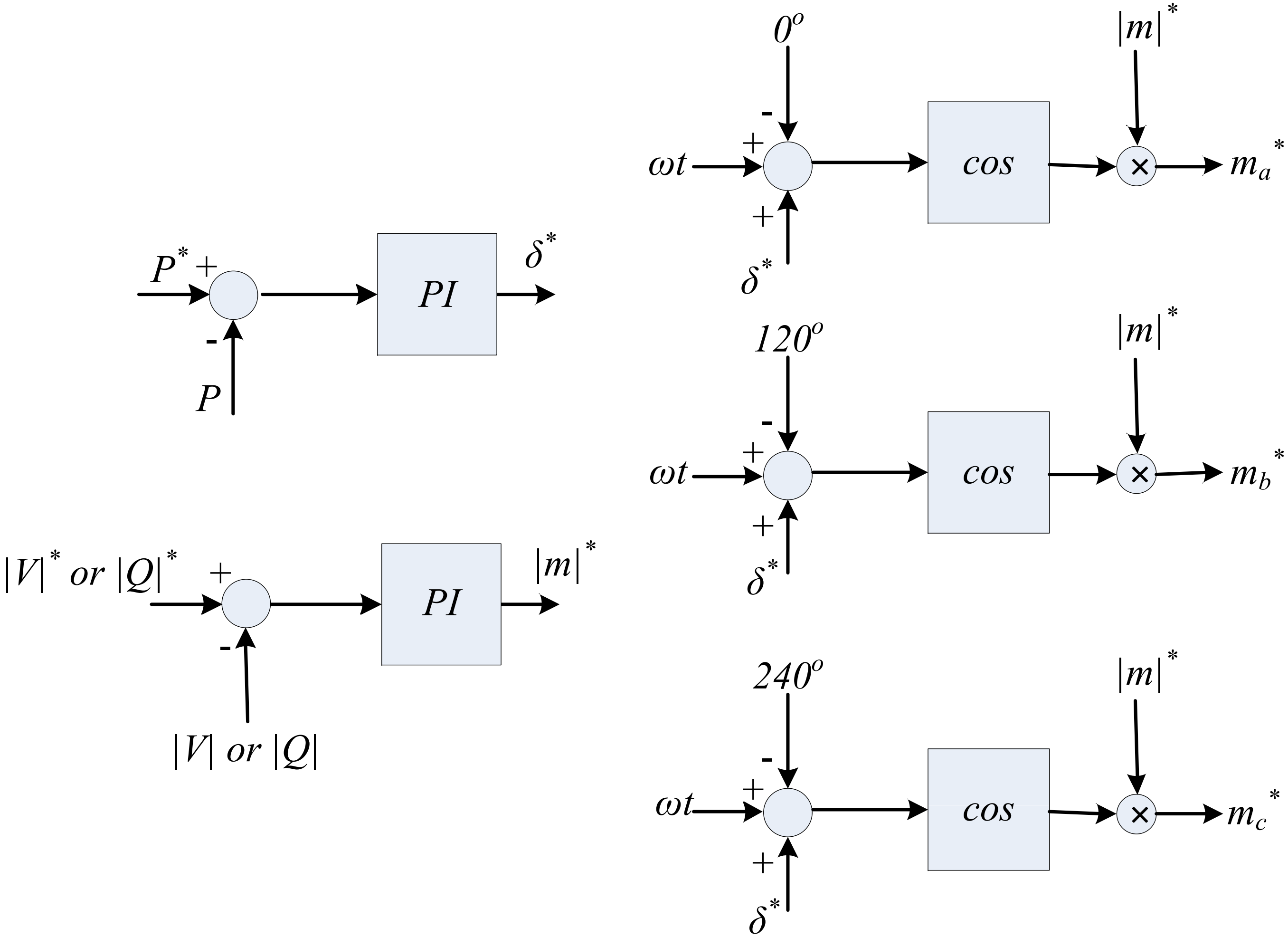
Control of VSC Connected to Active AC grid

Two options:

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

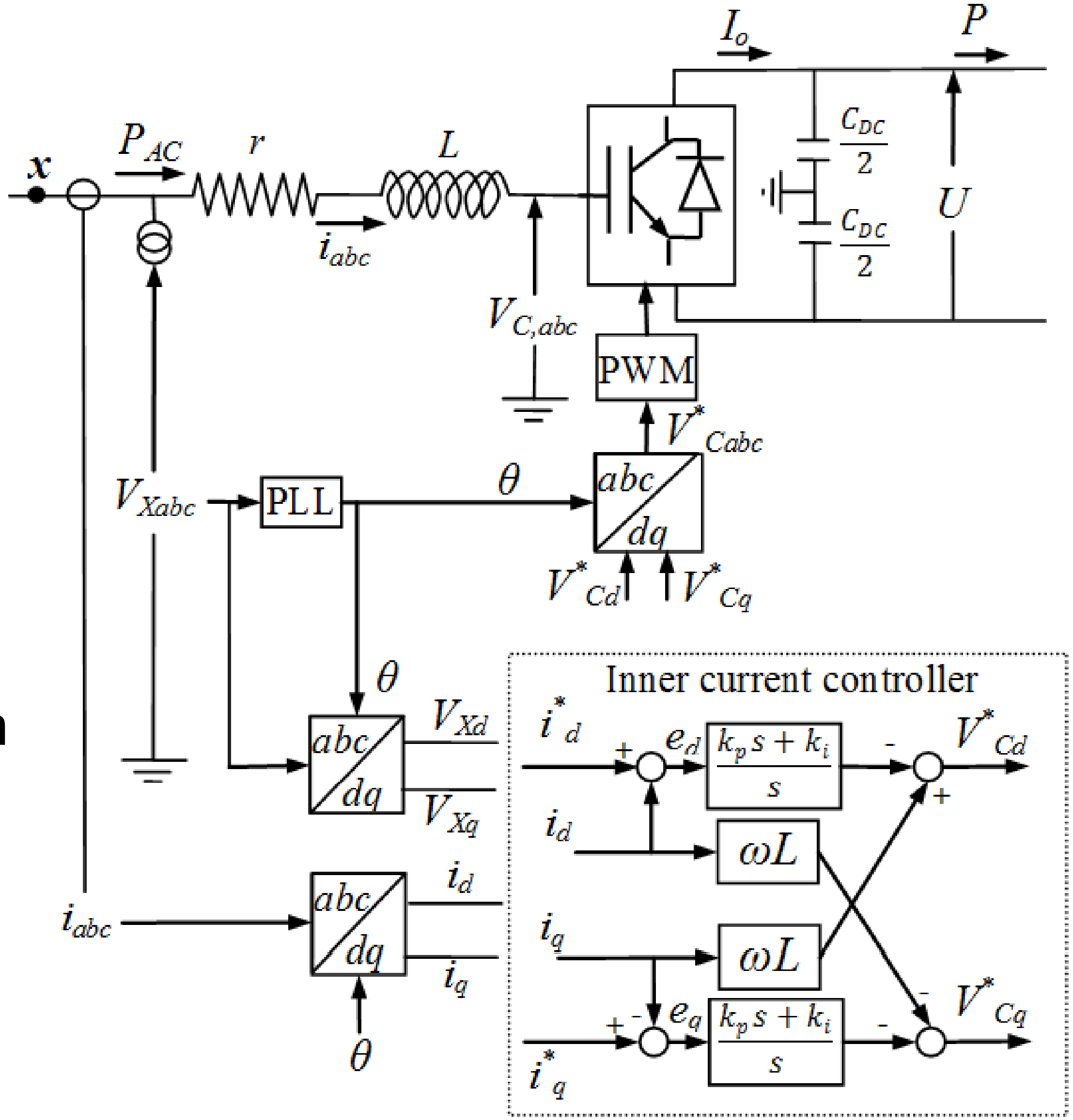
|m|, δ control

- 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



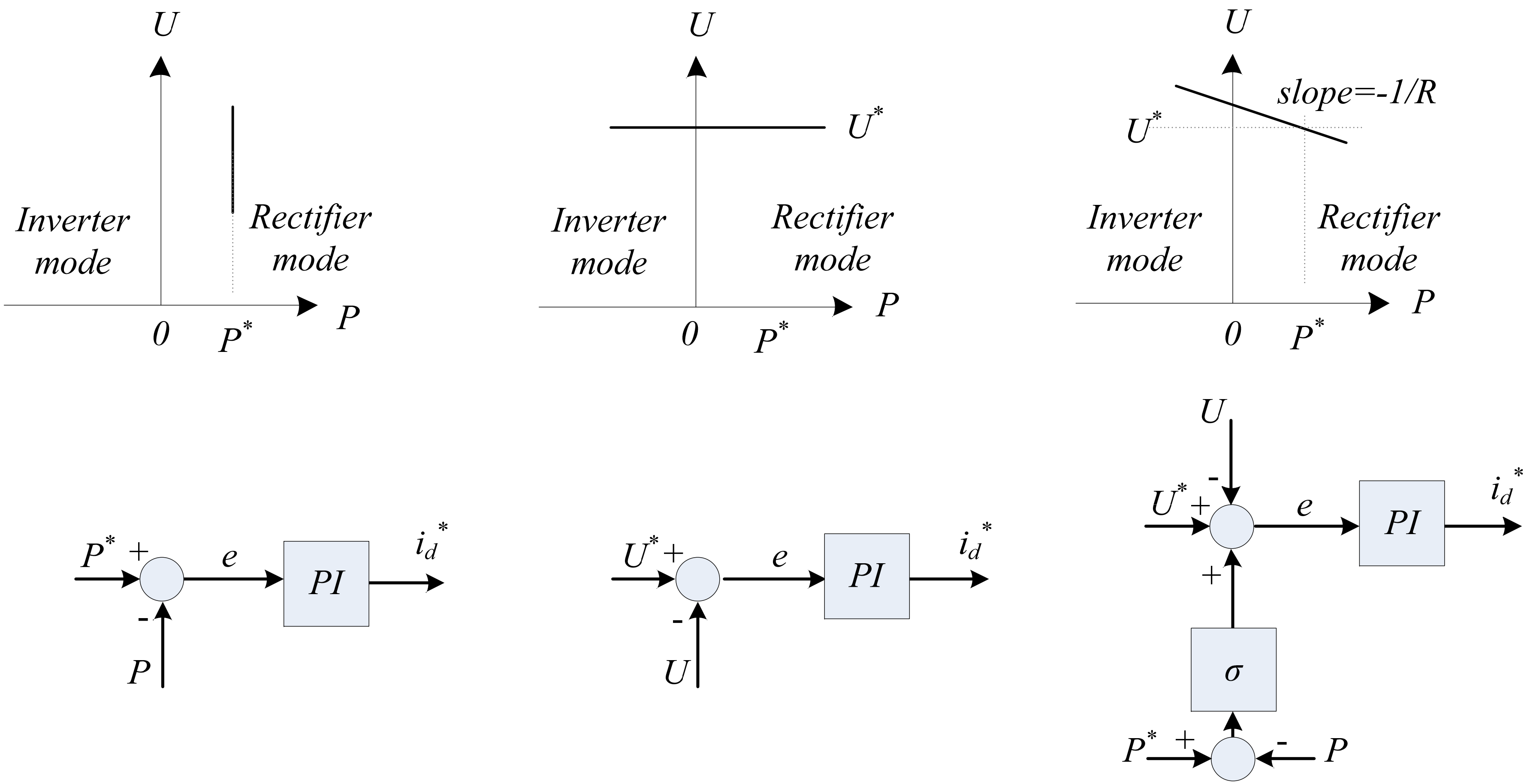
Decoupled axes (*dq*) control

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



Outer Controllers

- Set the references to active & reactive (inner) current controllers
- Active power and/or DC bus voltage control (there types shown below)
- Reactive power and/or AC voltage control (not shown here)



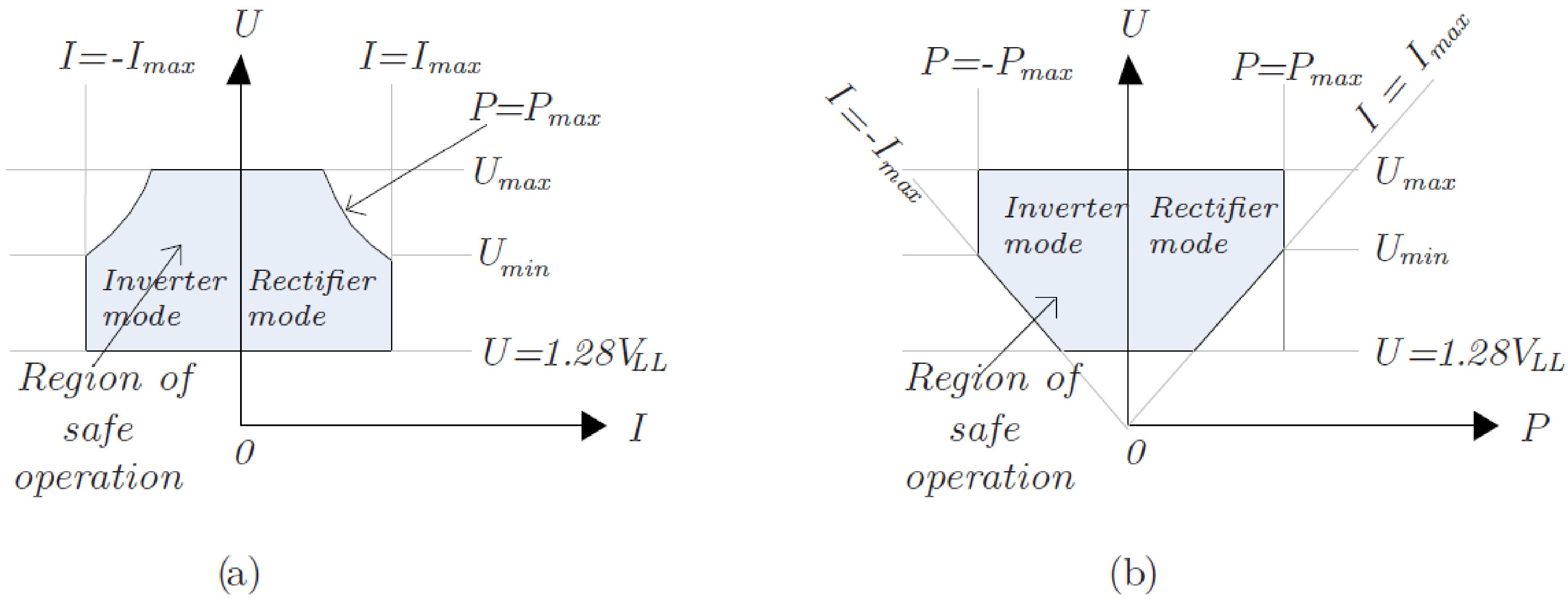
a. Fixed power control

b. Fixed DC voltage control

c. DC voltage droop controller

Safe operating area of a VSC

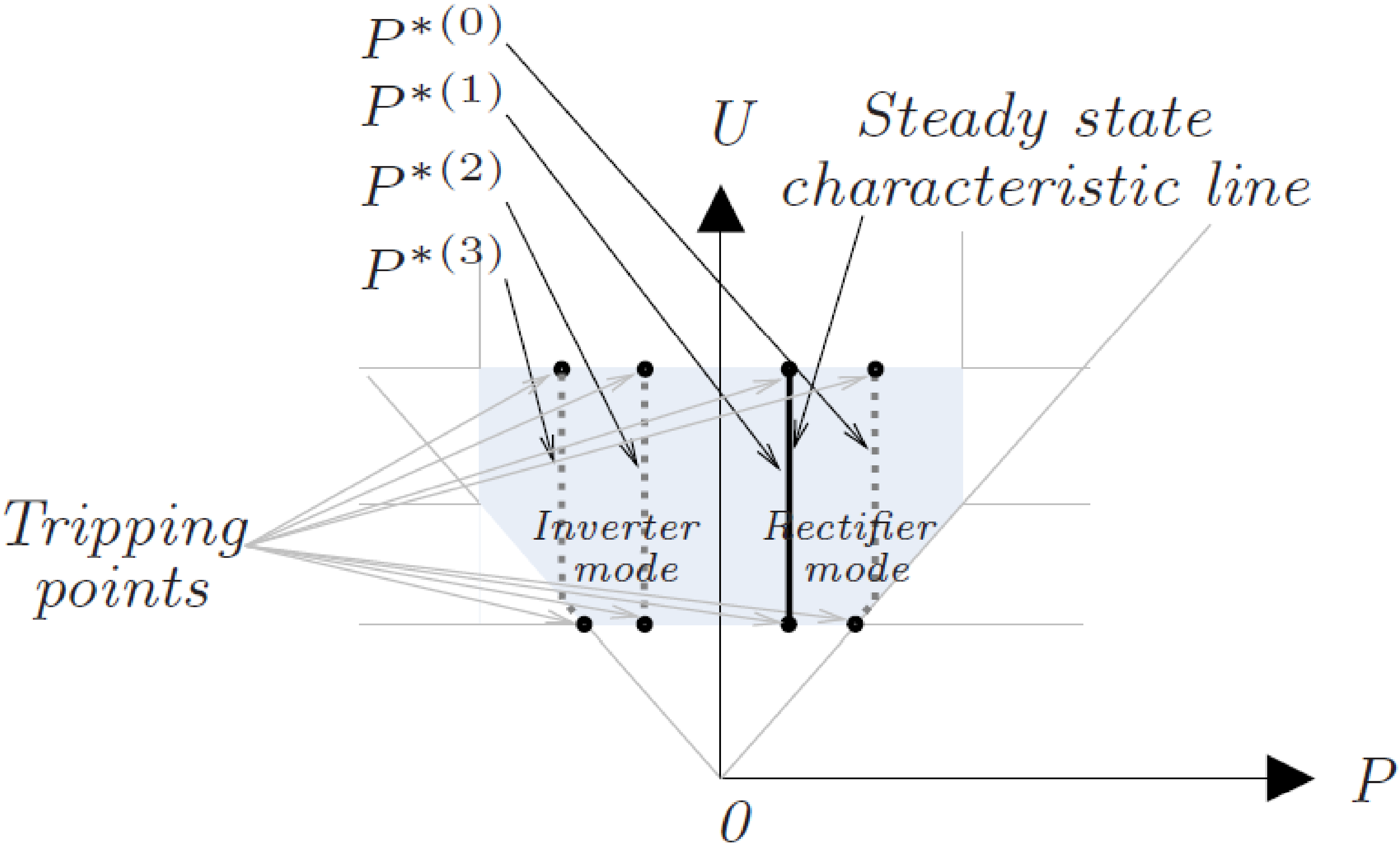
Controller actions are limited within safe operating area



Safe operating area of a VSC: (a) U vs I safe operating region (b) U vs P safe operating region

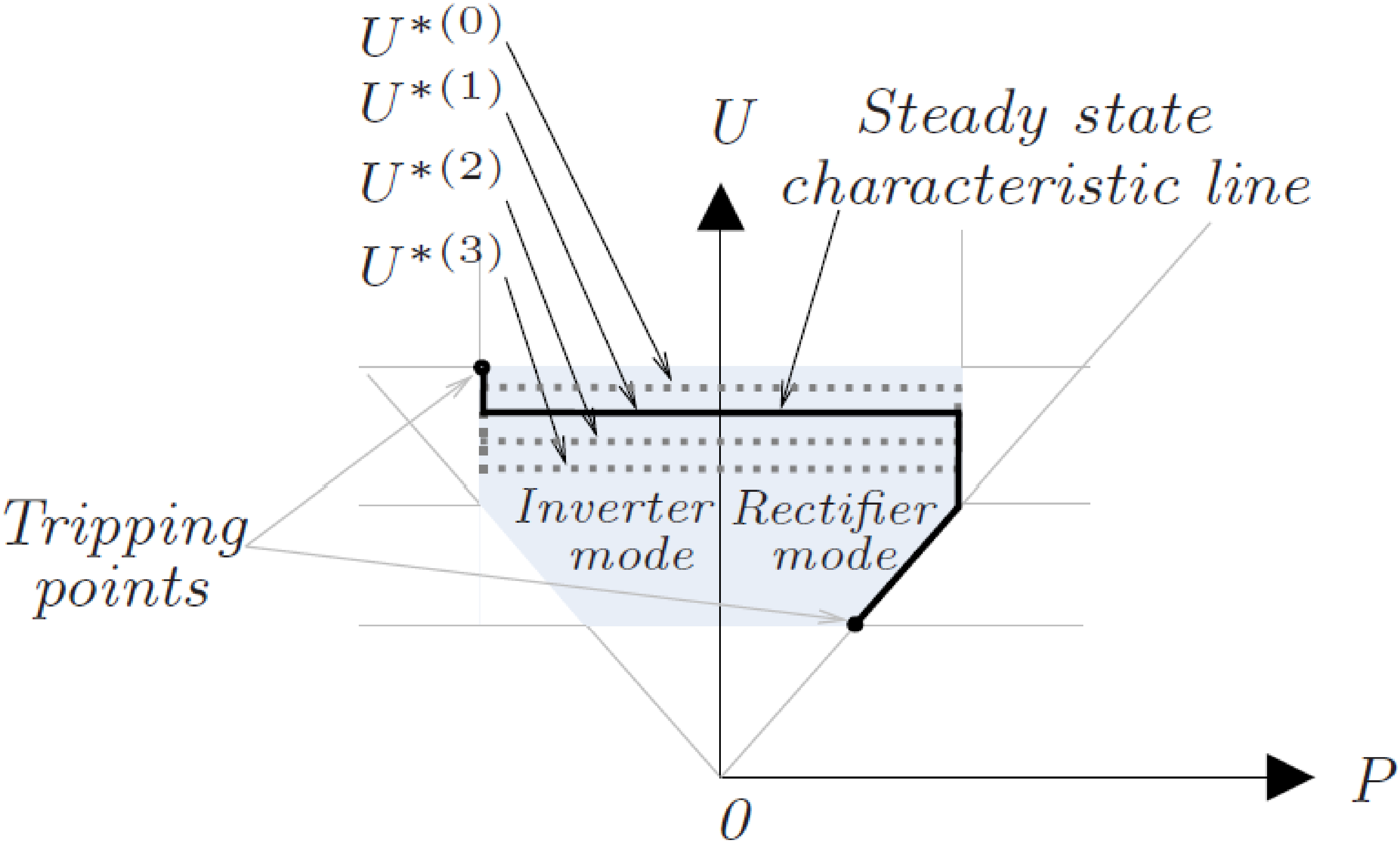
Constant power control within the safe operating region

P^* = power reference



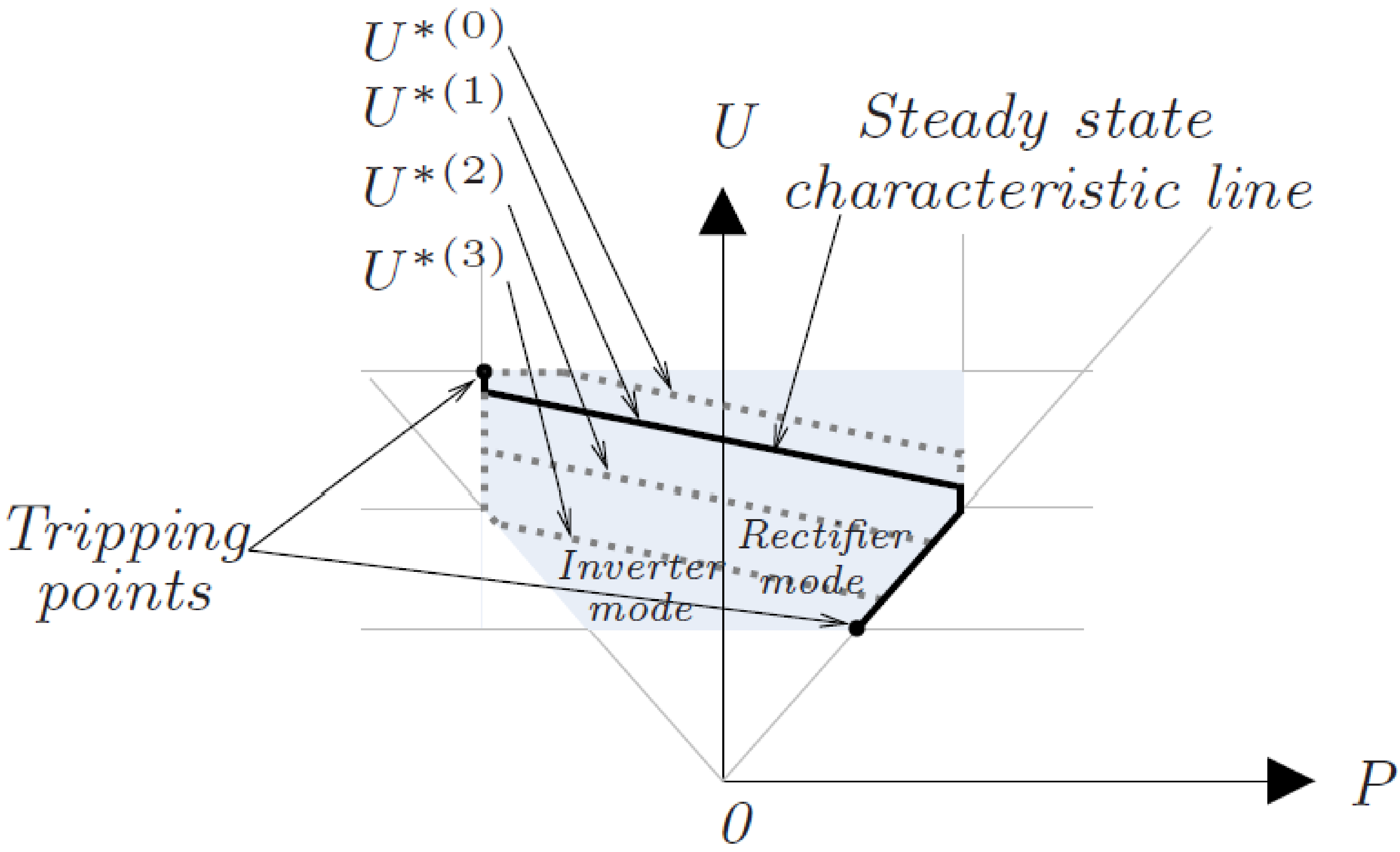
Constant DC voltage control within the safe operating region

U^* = DC voltage reference

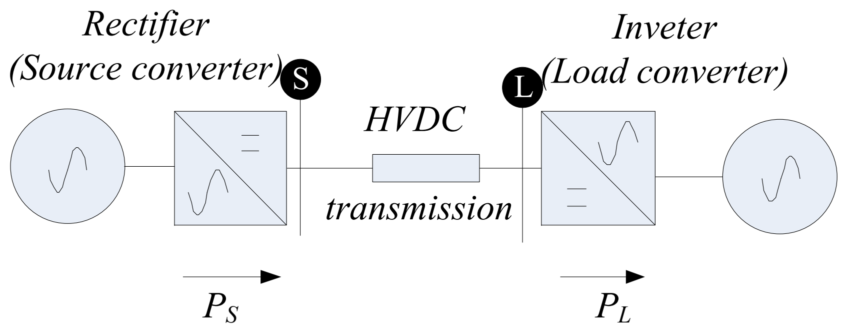


DC voltage droop control within the safe operating region

U^* = DC voltage reference



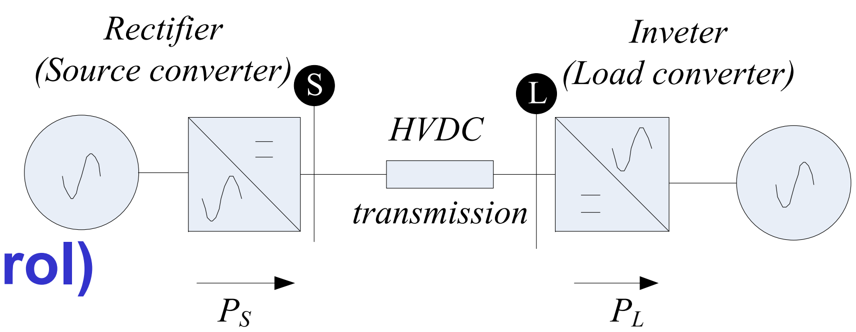
Two terminal VSC-HVDC Control

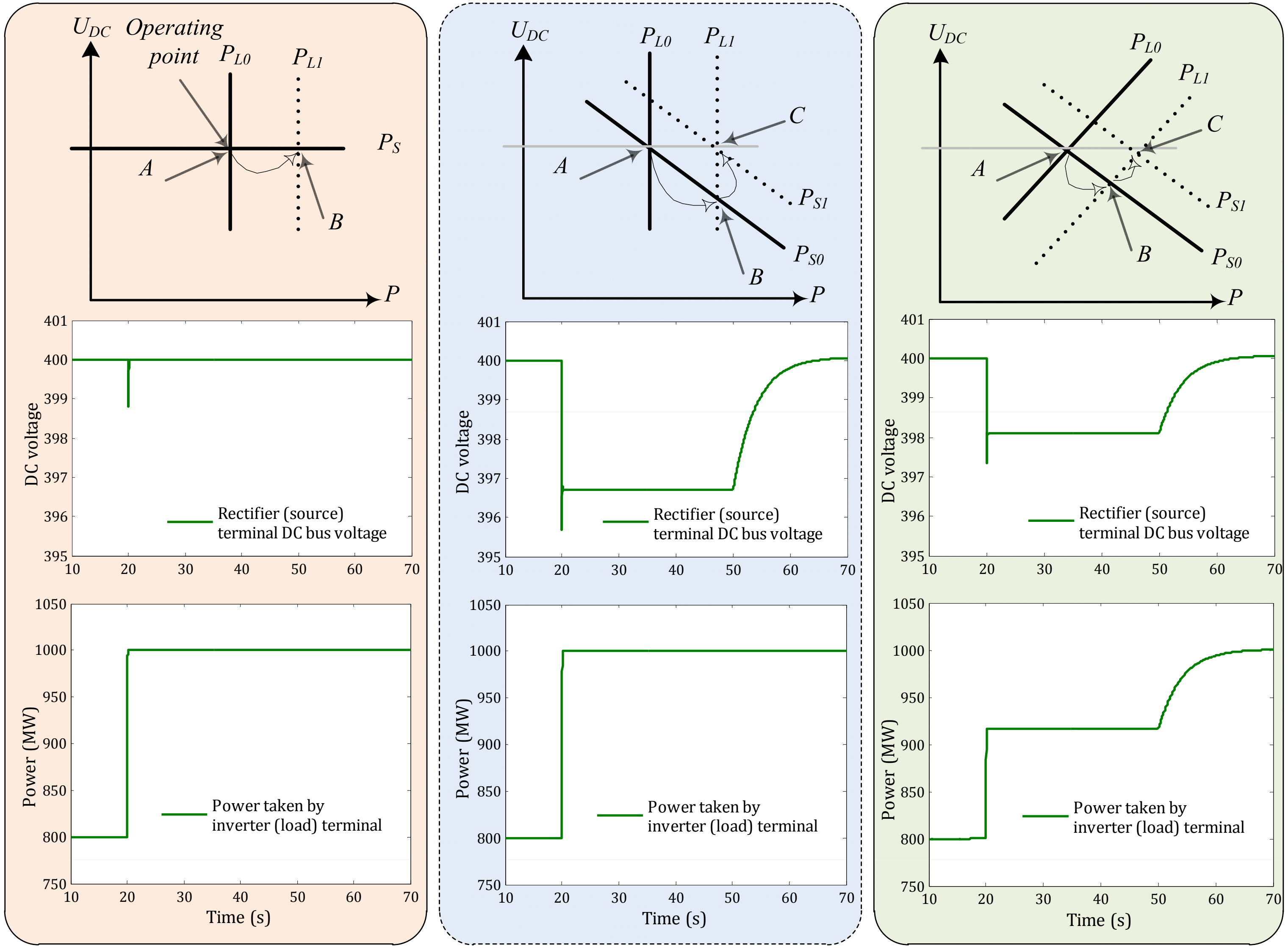


Control modes (3x3=9 combinations)		Remarks
Rectifier	Inverter	
Fixed power	Fixed power	X (Not viable)
Fixed power	DC Droop	√ (With risk of DC overvoltage)
Fixed power	Fixed DC voltage	√ (With risk of DC overvoltage)
DC Droop	Fixed power	√ (Good, P control by Inv.)
DC Droop	DC Droop	√ (Good, P control by Both)
DC Droop	Fixed DC voltage	√ (Good, 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)

DC Voltage Control Responses

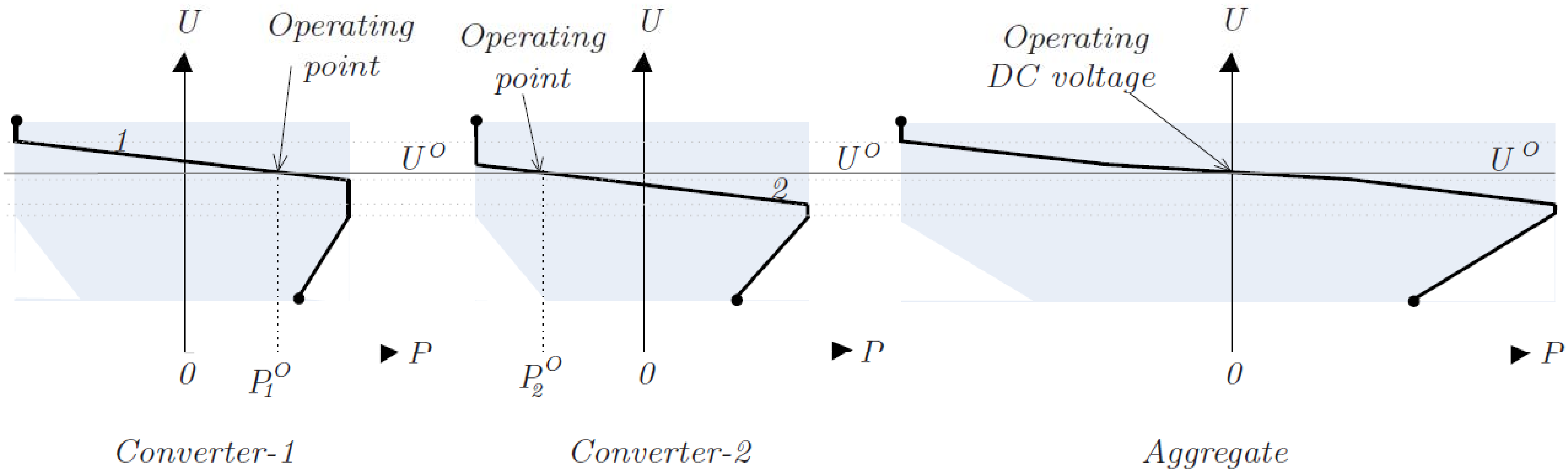
(Primary & secondary DC voltage control)





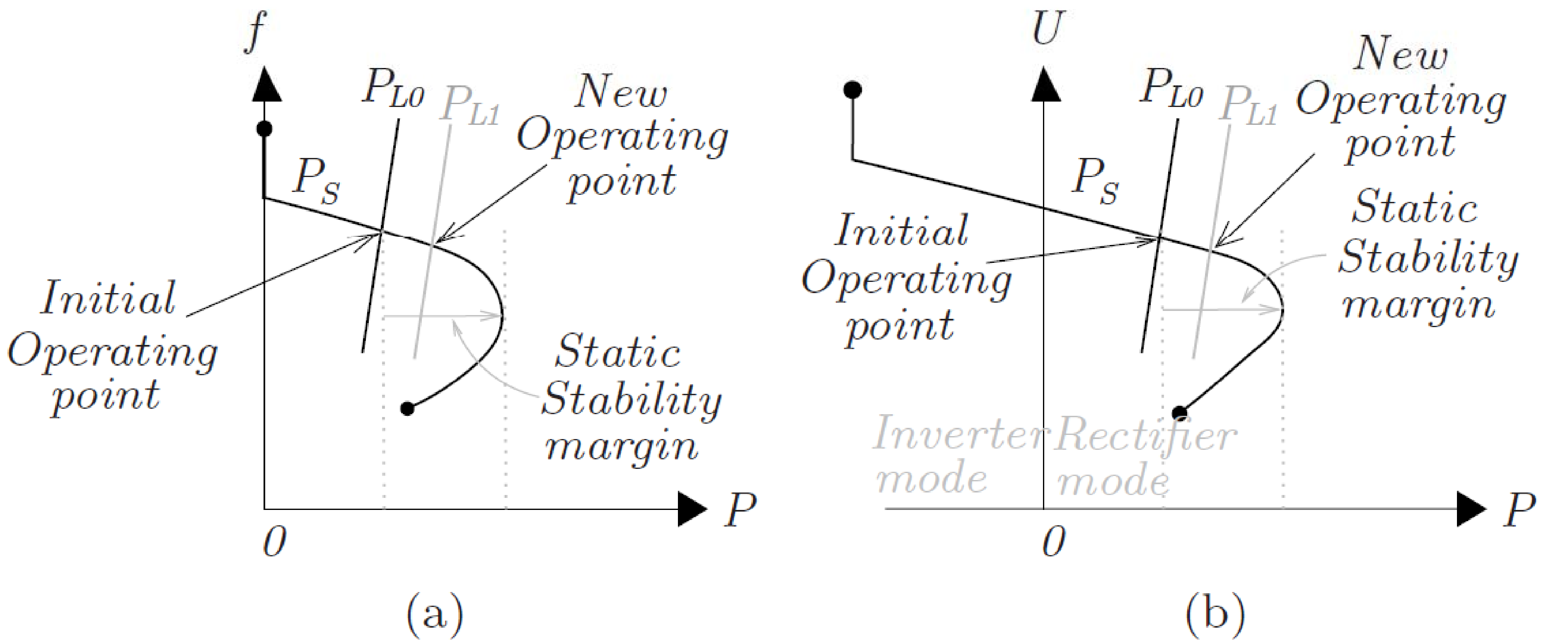
(a) (b) (c)

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



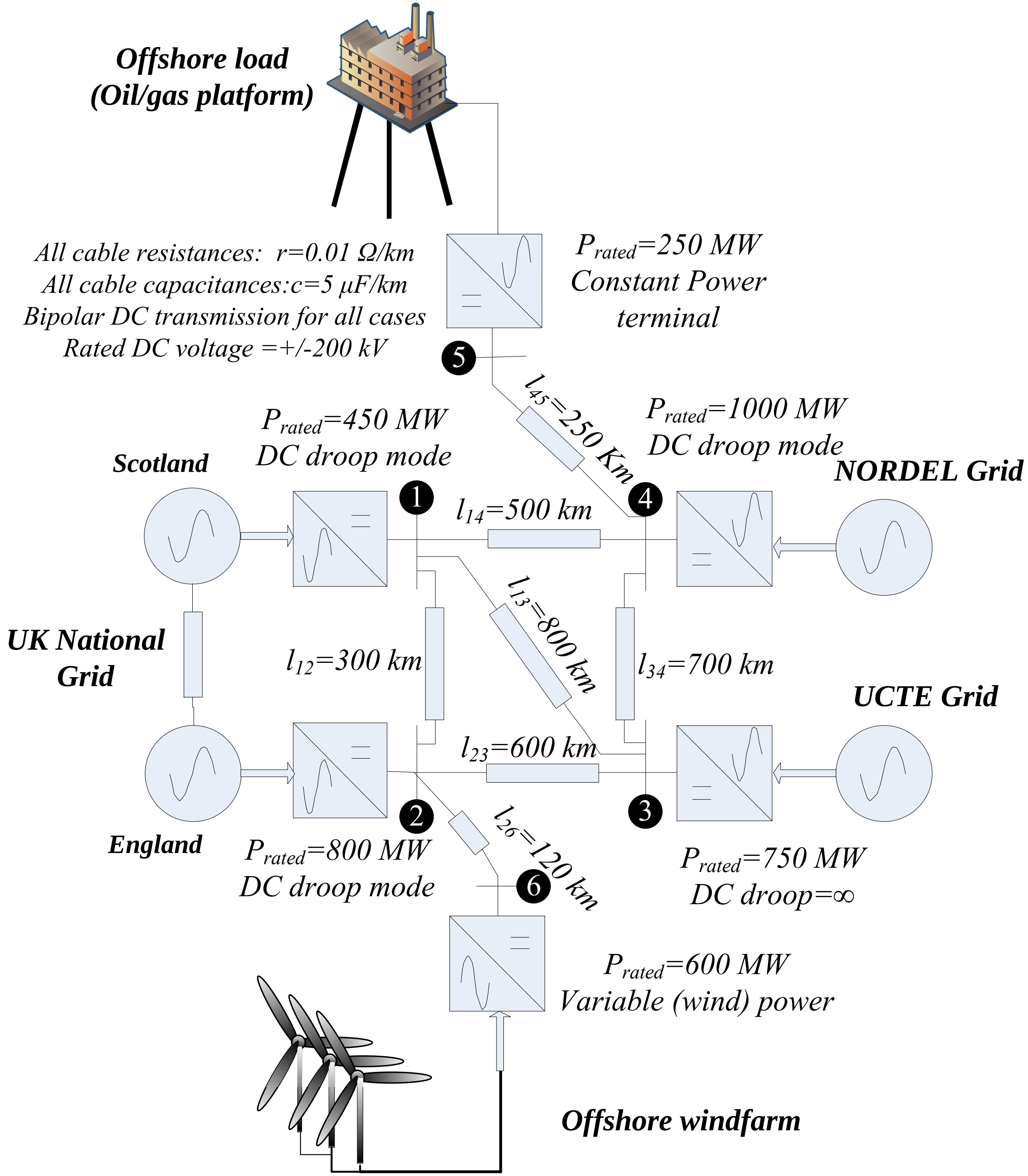
- No need for communication between terminals
- Many converter terminals contribute to DC voltage regulation
- DC analogy to distributed *frequency droop control* in AC systems

Similarities of AC grid frequency droop control and DC voltage droop control of MTDC



Steady state characteristic of: (a)synchronous generator (b)VSC-HVDC terminal (The dots at the end of the characteristic lines show tripping points.)

Test model: "North Sea DC grid"

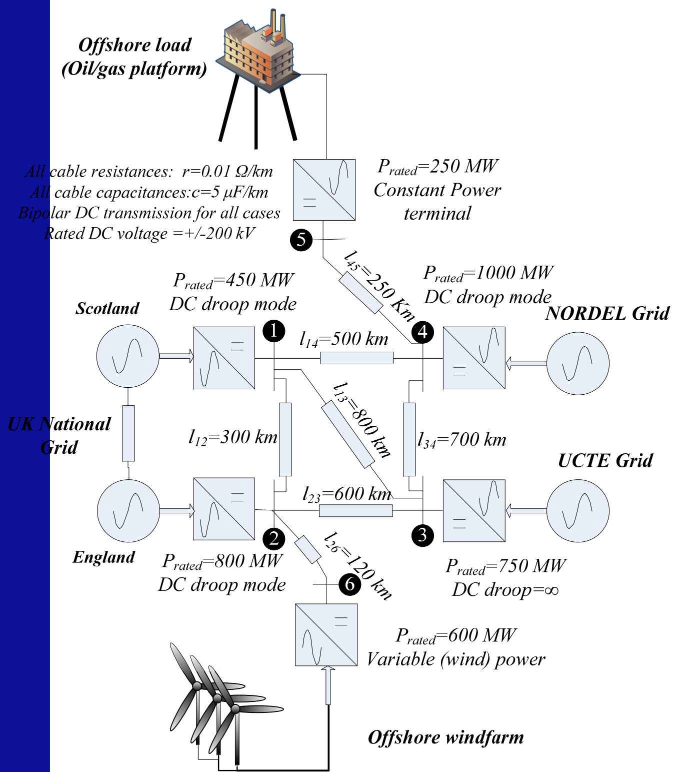


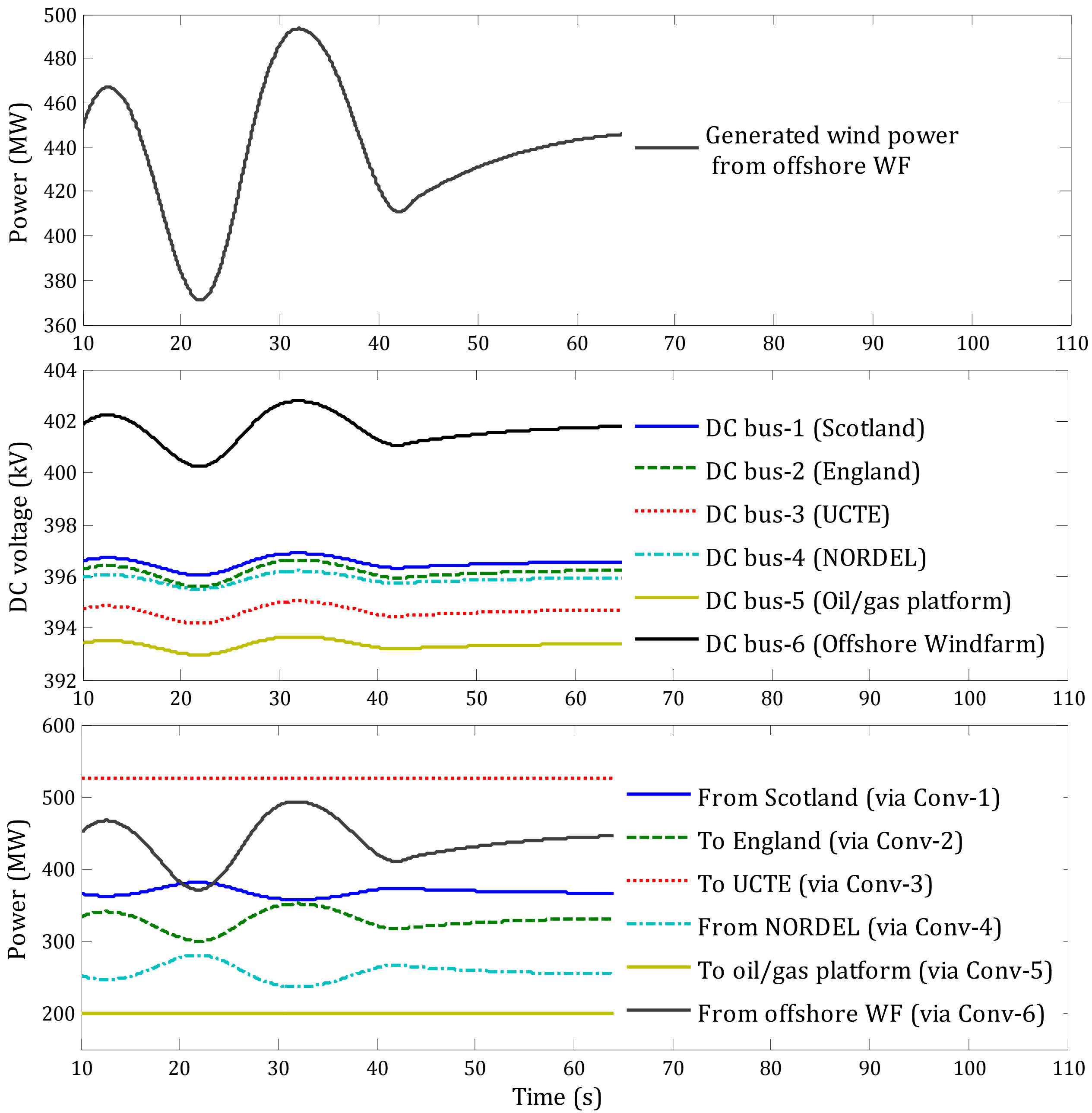
Security analysis

Examples illustrating security aspects related to operation and control

- Managing normal wind variations
- Outage of DC connections
- Outage of generation (wind farm tripping)
- Primary control response to ac grid contingency (exchange of primary reserves)
- Need for secondary control

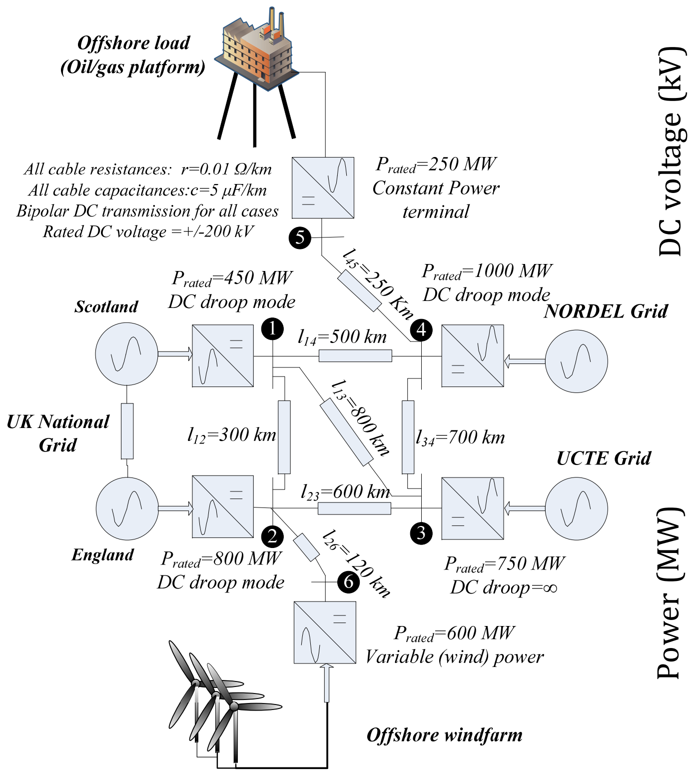
Variations of DC voltage with fluctuating wind power and DC droop control responses

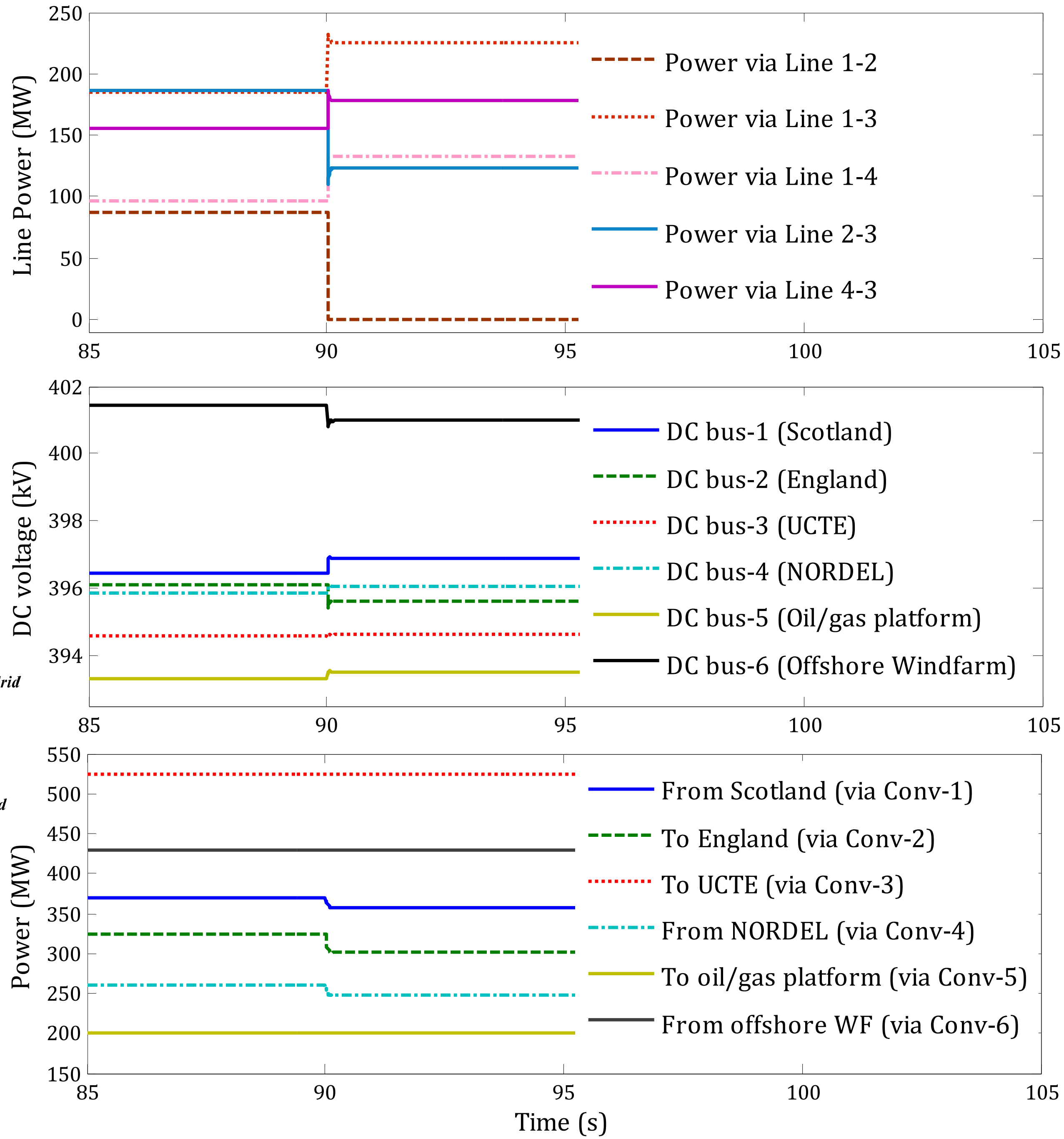




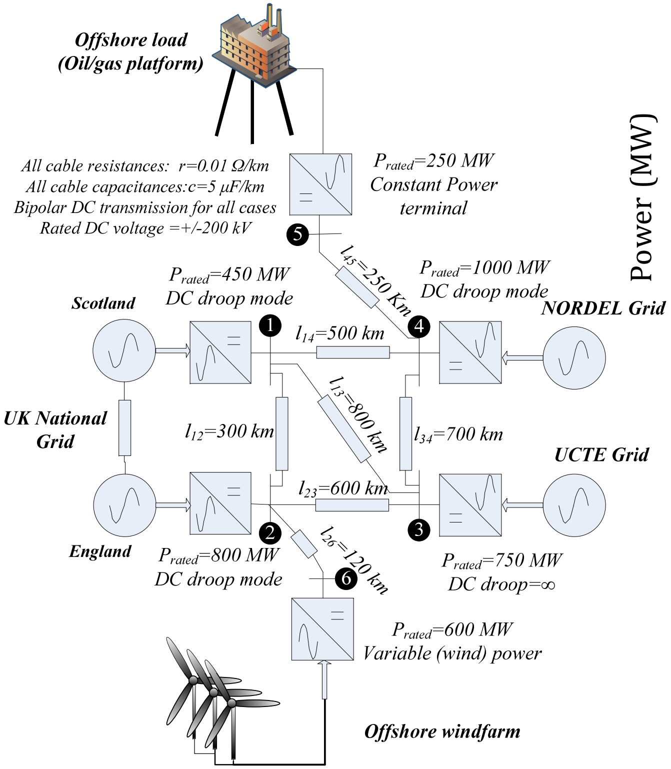
Outage of DC line 1-2

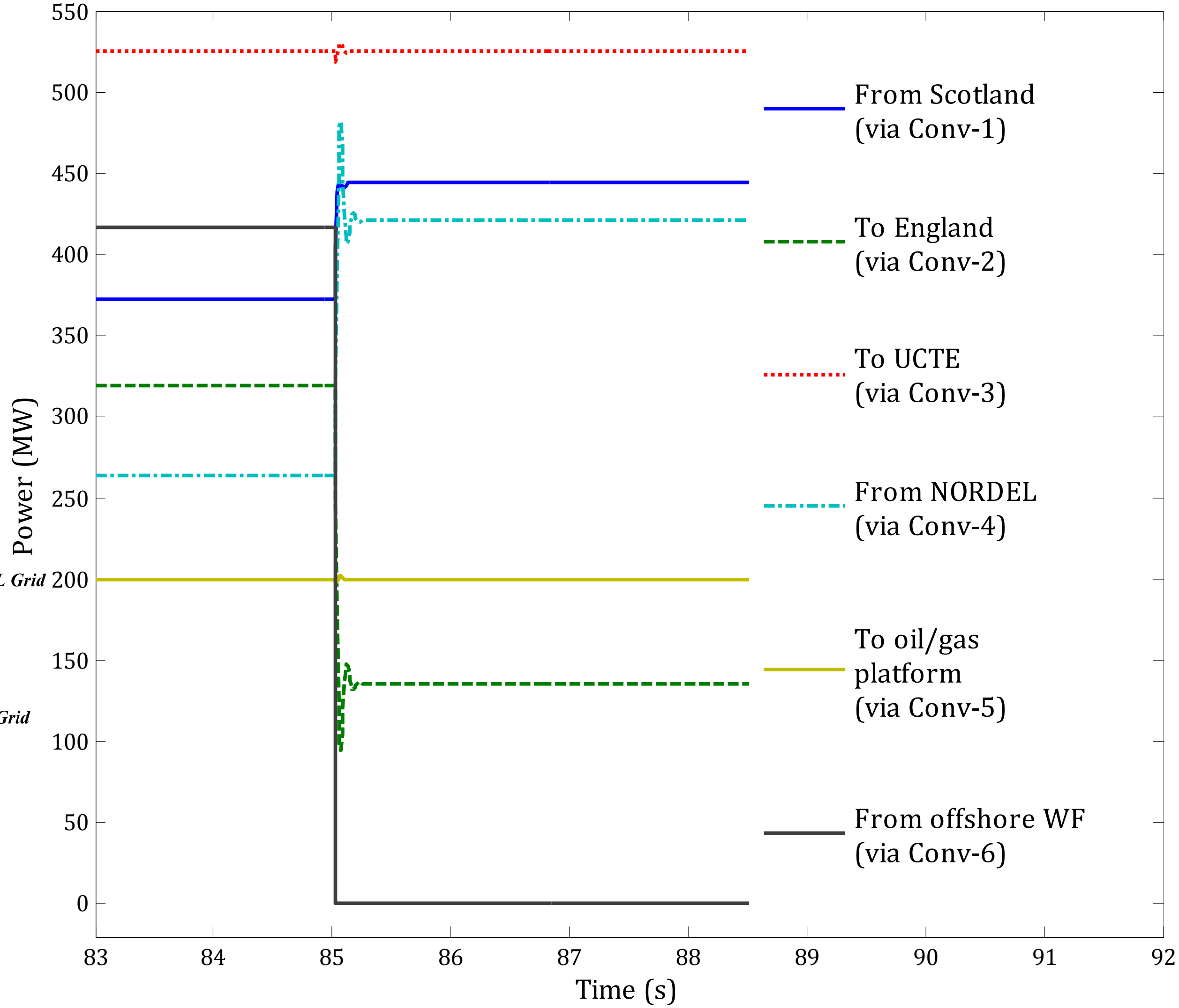
Terminal-1 (Conv-1) continues to draw power from DC grid via lines 1-3 and 1-4 when line 1-2 is disconnected.





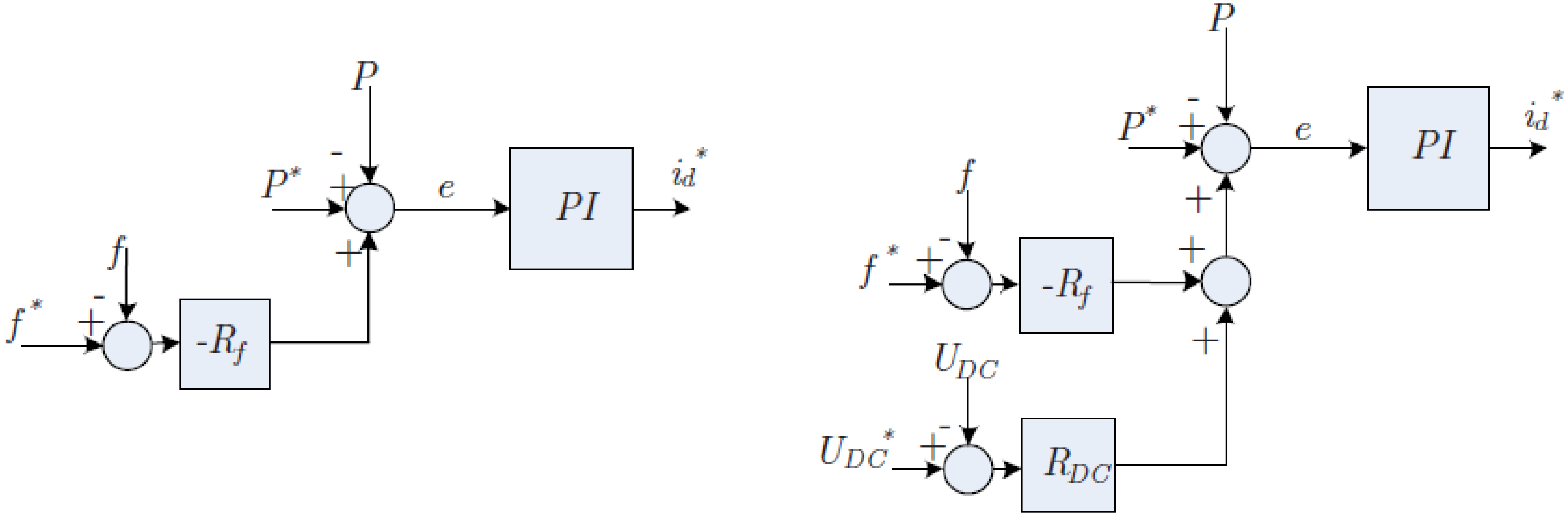
Outage of connection to windfarm





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

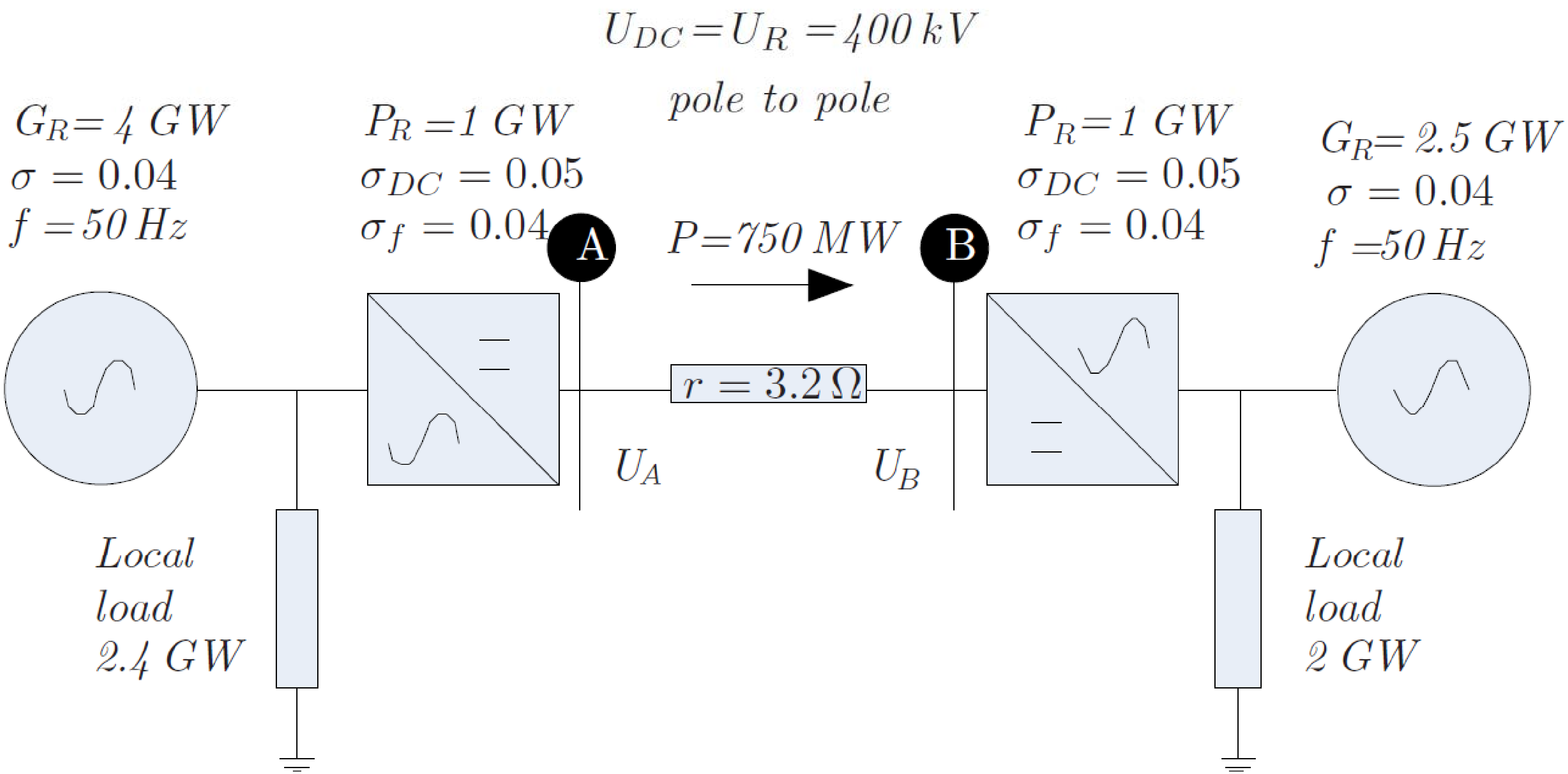
Frequency response enhancement of AC grids by VSC-HVDC



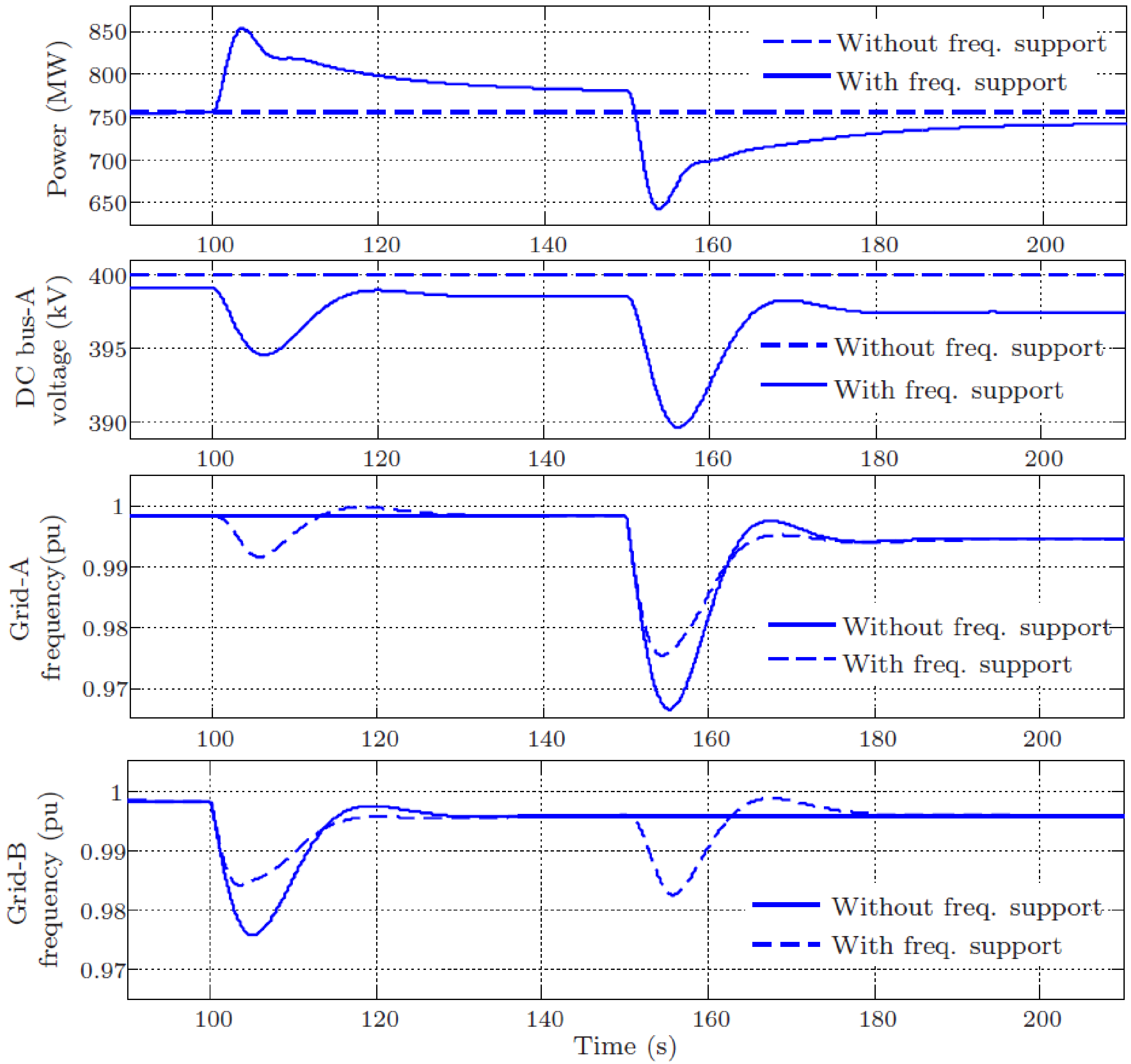
(a) (b)

Frequency droop control implemetation on VSC-HVDC with:
(a) constant power control (b) DC voltage droop control

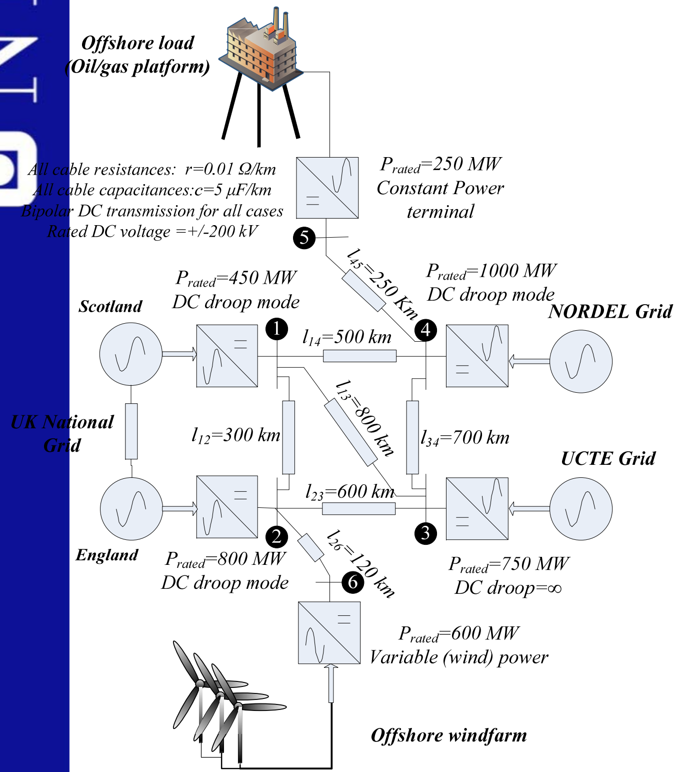
Frequency response enhancement example: two terminal VSC-HVDC

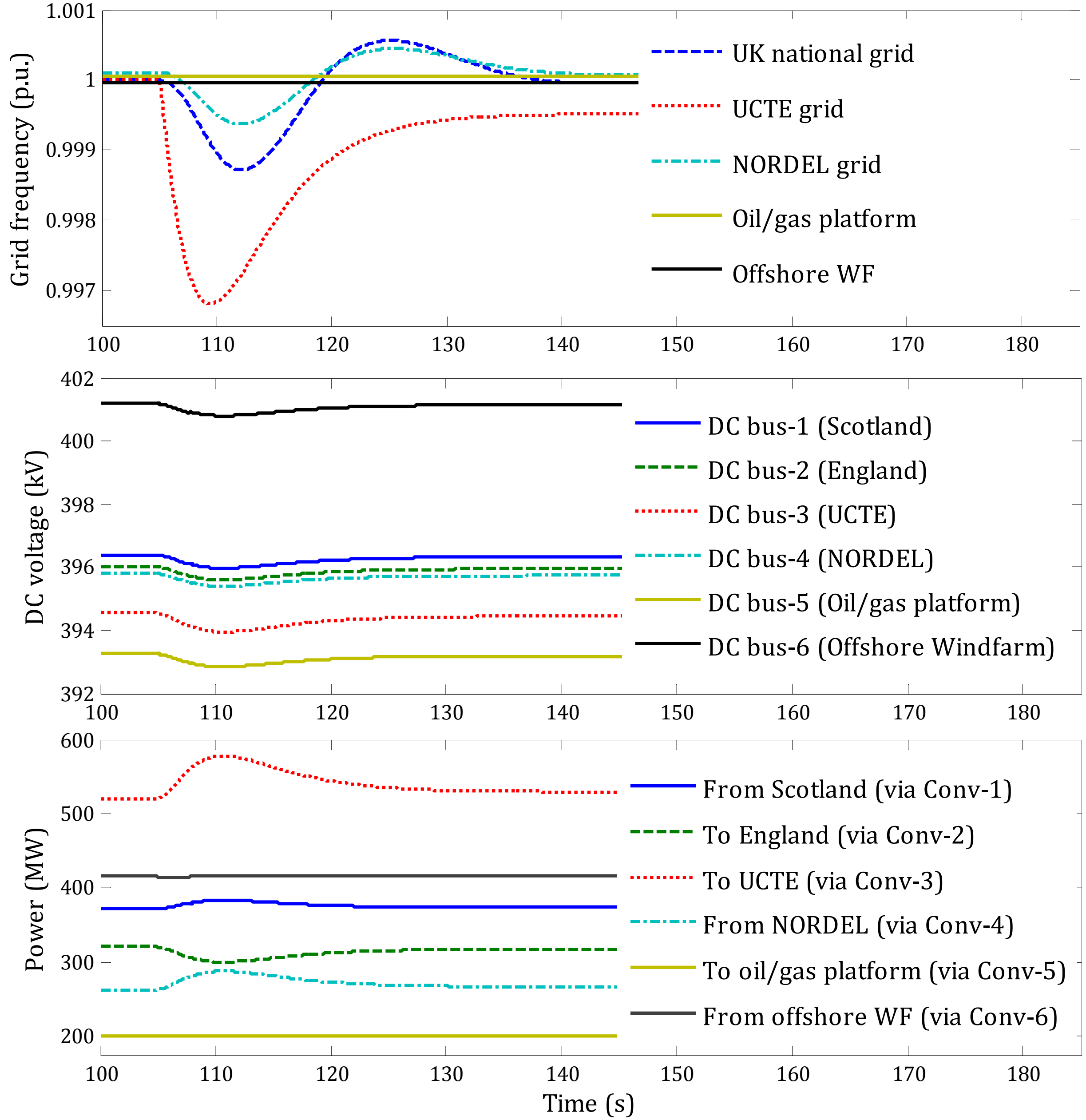


Effect of frequency droop control (in VSC-HVDCs) on AC grid frequency responses



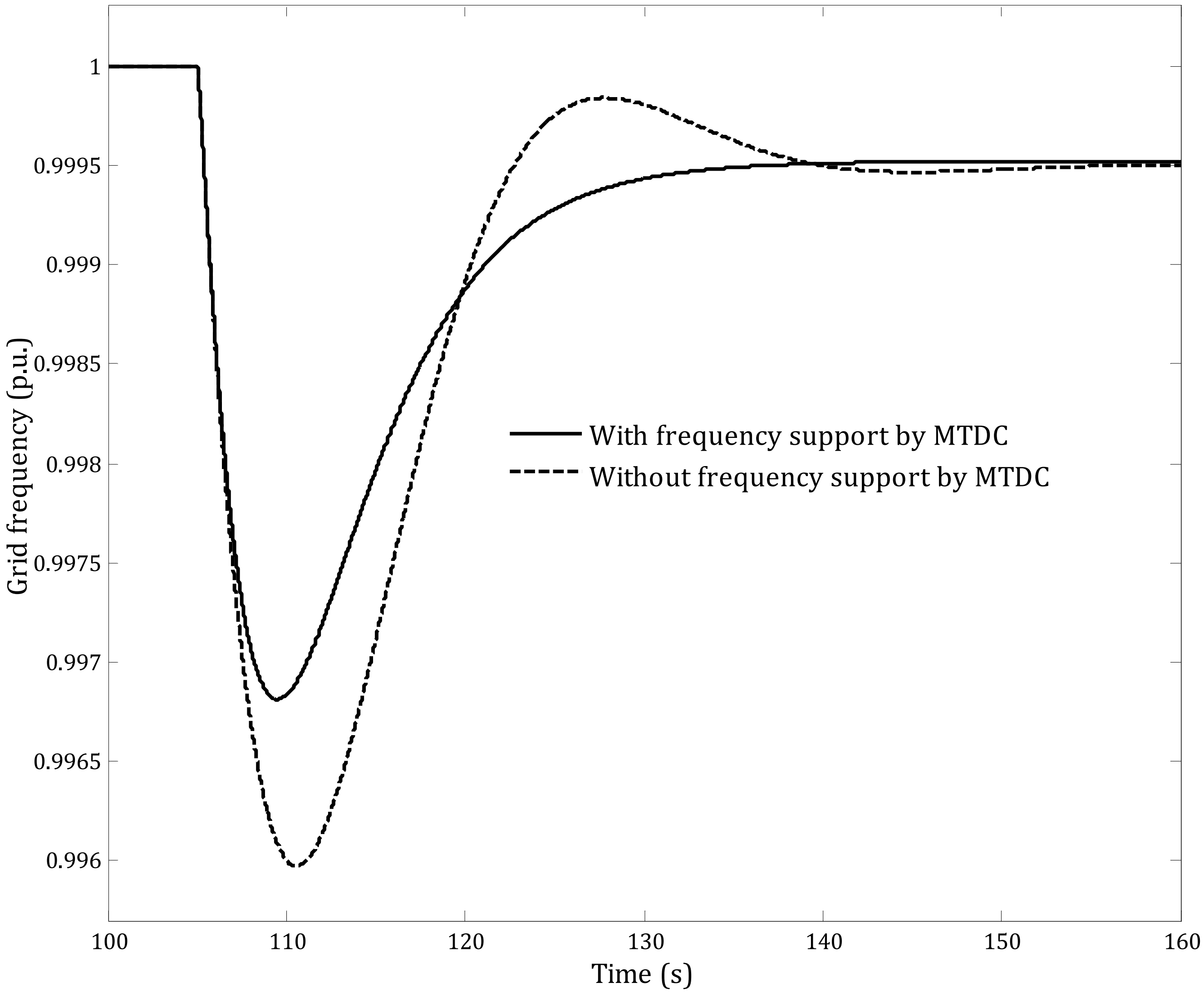
Frequency response enhancement of AC grids by MTDC





UCTE grid frequency supported by NORDEL and UK (via two HVDC stations: one at England and the other in Scotland)

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

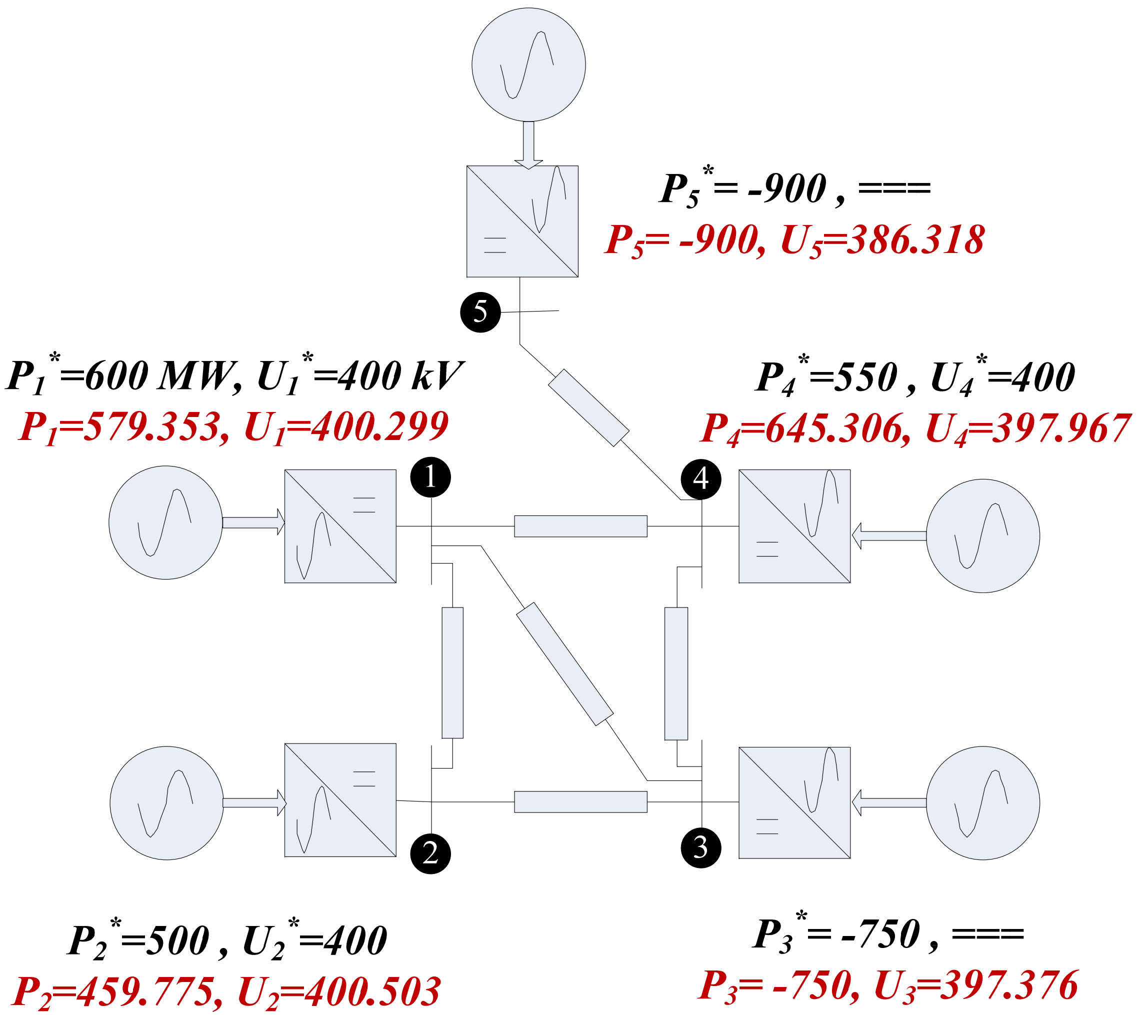


Frequency response improves with presence of frequency support from DC grid.

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



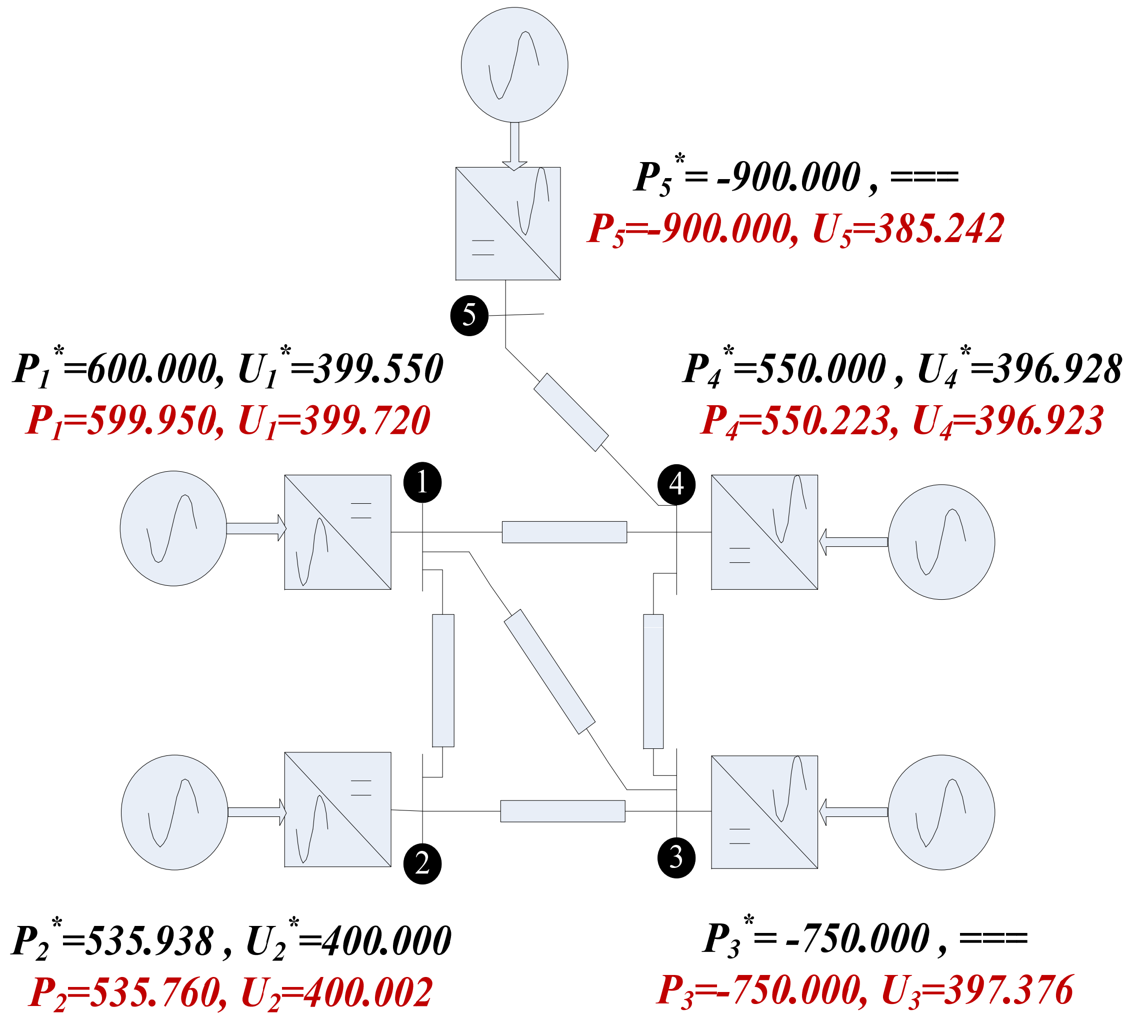
Not precise!

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

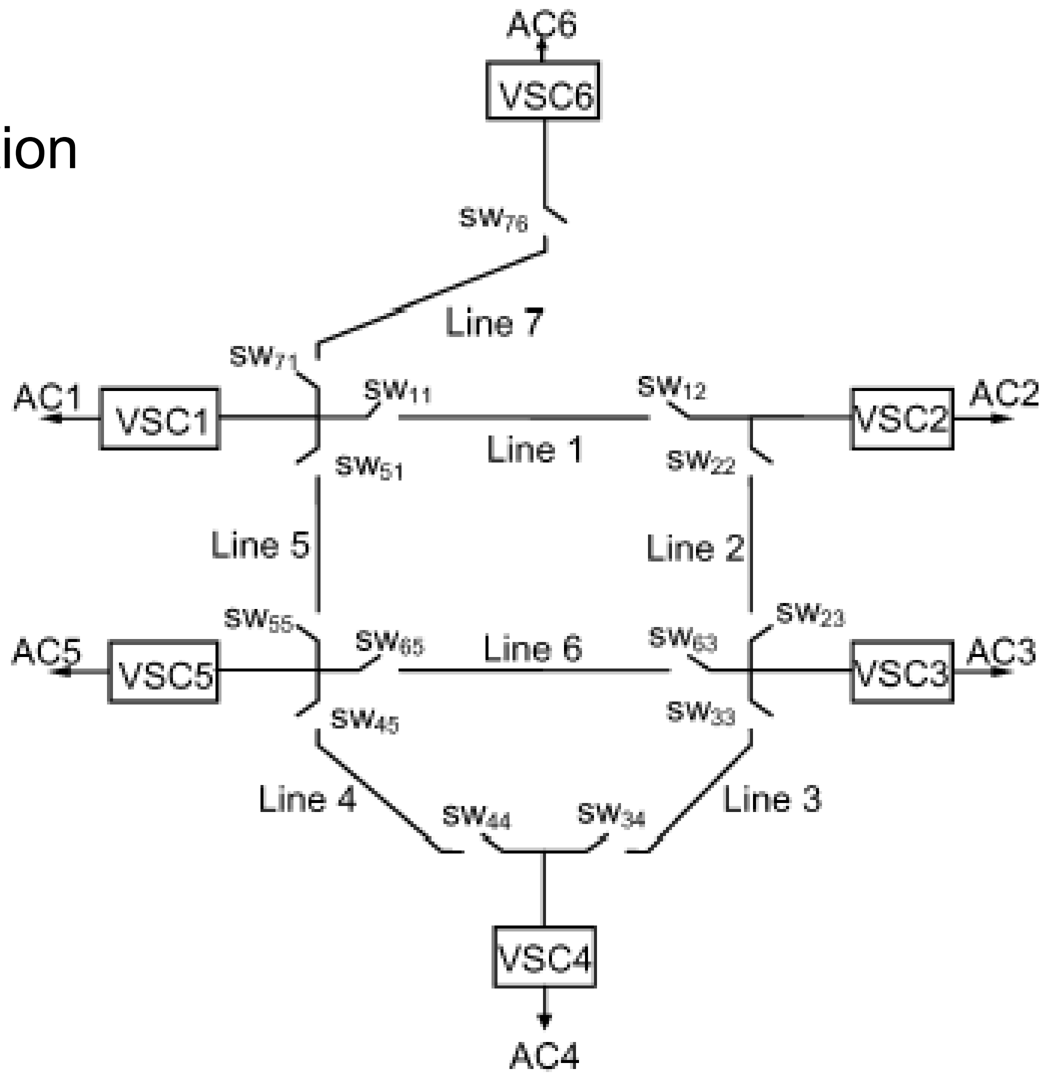


Precise!

(Desired power flow achieved)

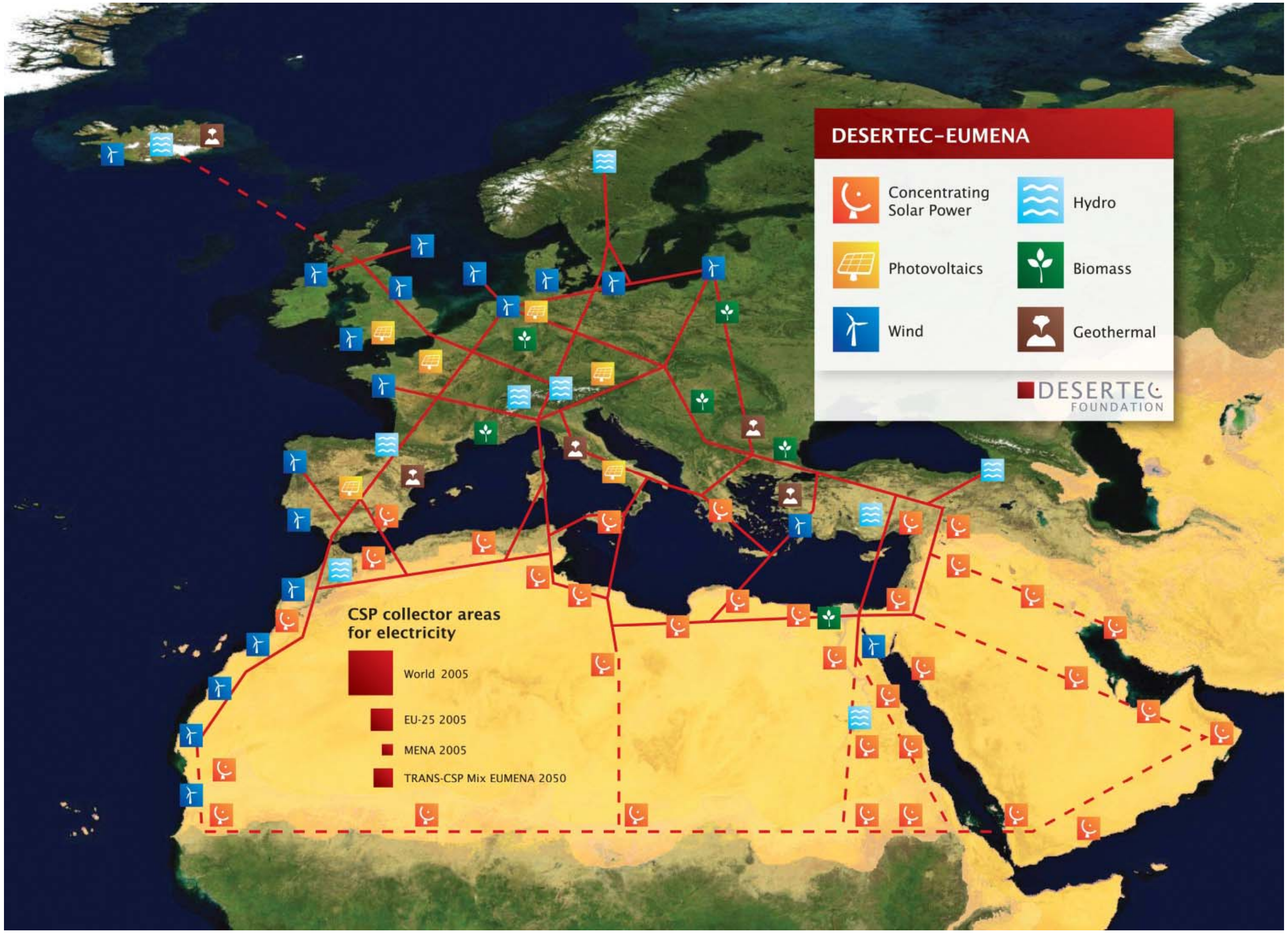
Future works on MTDC

- Protection schemes
- Fault detection and localization algorithms
- Communication based (?)



Future works…

Impact of wide area MTDC (Stability, operational, …)



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Thank you!