DC technology and Systems

DC grids control (II)

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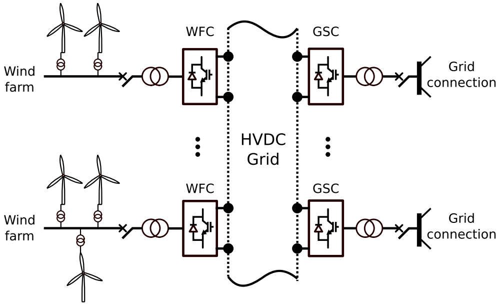
Outline of the presentation

1. Multiterminal grid control
2. Multiterminal HVDC grids modeling
3. Multivariable droop control analysis
4. Four terminal grid example

Outline of the presentation

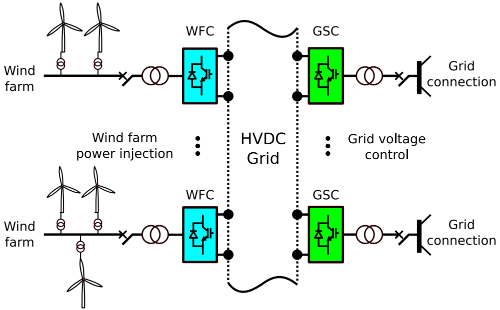
HVDC power transmission - Offshore wind farms



Multiterminal Grid elements

- Wind farms
- Main AC Grid connections
- Wind farm converters (WFC)
- Grid side converters (GSC)
- HVDC multiterminal grid

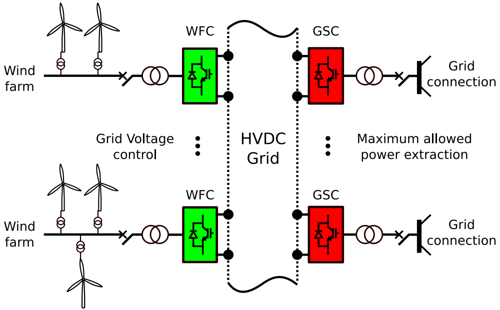
Grid control - Normal operation



HVDC multiterminal grid control

- Droop control performed by GSCs regulates the DC voltage
- WFCs inject to the HVDC grid all the incoming power from the wind farms

Grid control - Grid fault operation



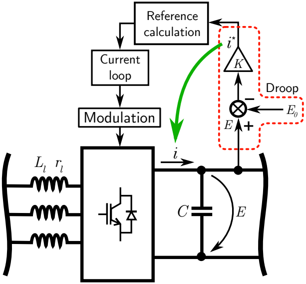
HVDC multiterminal grid control

- GSCs extract the maximum possible power without exceeding their limits.
- Droop control performed by WFCs regulates the DC voltage

The droop control

Characteristics

- Proportional control nature.
- Implemented at each of the VSC-HVDC converters.
- Applied through the converter current loop.



- Equation:

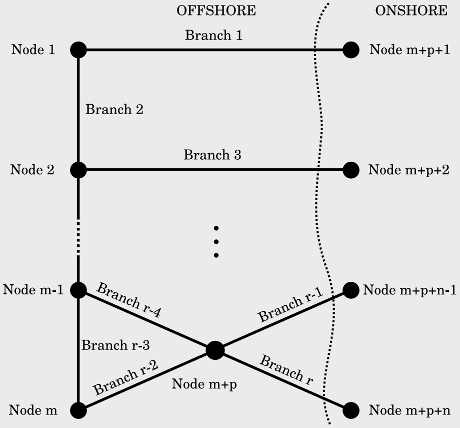
$$i^* = K(E - E_0)$$

- It is considered that the current i is equal to i^* assuming that the current loop performance is faster than the HVDC grid dynamics.

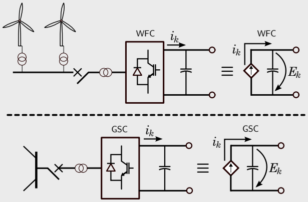
Outline of the presentation

Multiterminal modeling

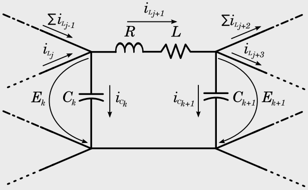
Multiterminal grid



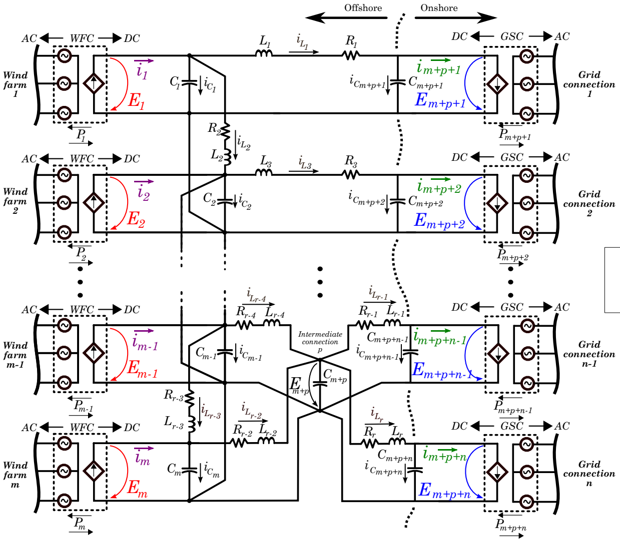
Input-Output power nodes



Branch



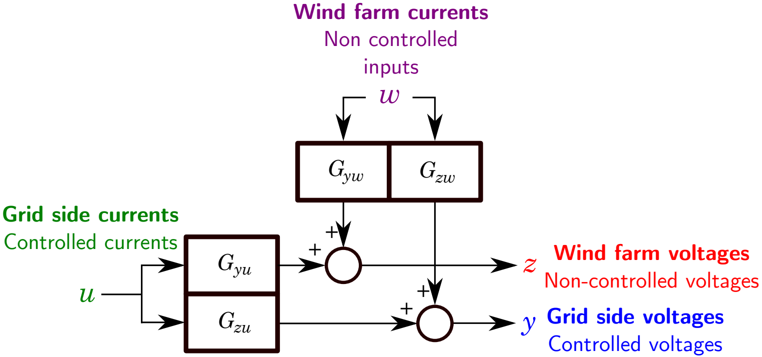
Complete grid modeling - Normal operation



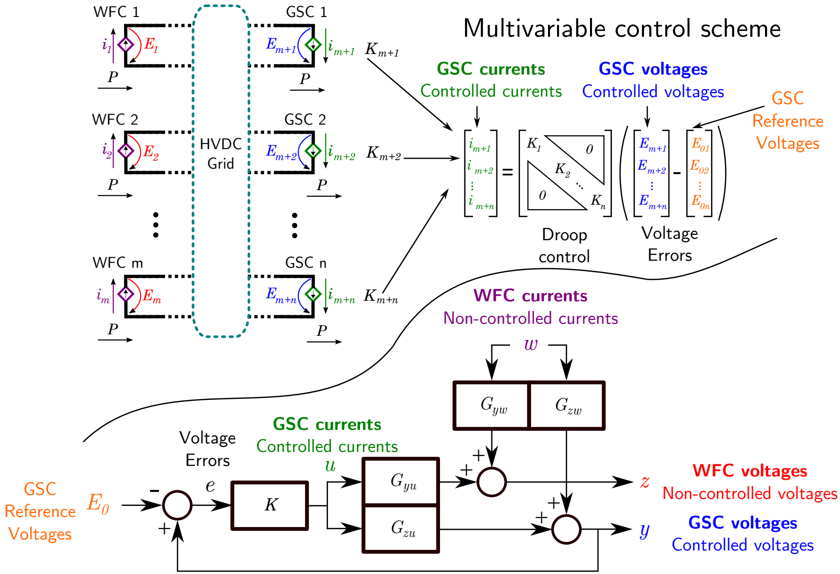
[GSC]
Controlled currents [u]
Controlled voltages [y]

[WFC]
Non-controlled currents [w]
Non-controlled voltages [y]

Open loop transfer function matrices



Outline of the presentation

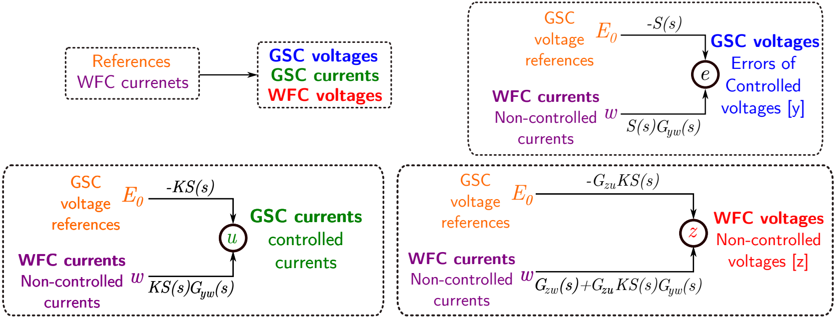


How can we calculate these constants?

Closed loop control scheme

Closed loop transfer function analysis

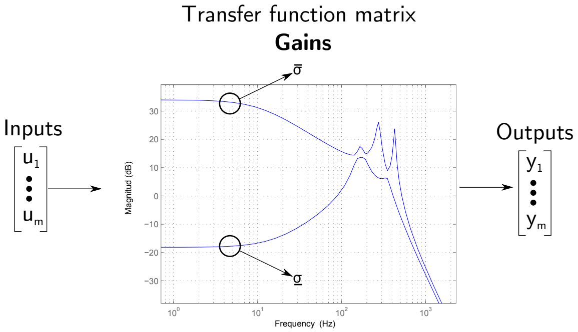
- These matrices show how the **system inputs** affect other system variables
- Frequency methods are used to analyze these transfer function matrices



Frequency response analysis for droop gain selection

Singular value representation

- Used for multivariable system analysis
- It is an extension of the bode diagram used for SISO system analysis
- Shows for a range of frequencies, the maximum and minimum gain curves

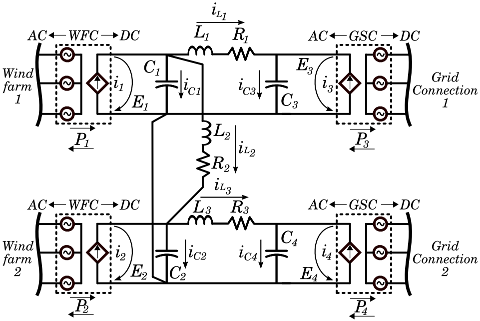


Outline of the presentation

Four terminal grid example

Four terminal grid

- Two Wind farms and Two Grid connections
- Grid specifications
  - Nominal grid voltage: 150 kV
  - GSC/WFC power: 100 MVA



Case studies

- Case 1: Grid operated under normal conditions
- Case 2: Grid operated during an AC fault

Criteria for defining the multivariable droop control

Controller performance specifications

- Inject to the grid all the incoming power from the wind farms
- Power sharing between nodes controlled by means of droop
- Maintain the DC voltage within grid limits
- Maintain the DC currents within grid and converter limits

Using the **multi-variable frequency analysis** theory the droop controller constants can be selected.

Case 1: Droop AC side
Variables definition

WFC voltages [Non-controlled voltages]

$$z = \left[E_1 E_2\right]^T$$

GSC voltages [Controlled voltages]

$$y = \left[E_3 E_4\right]^T$$

Voltage references:

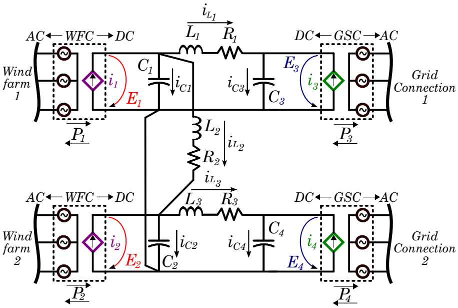
$$E_0 = \left[E_{03} E_{04}\right]^T$$

WFC currents [Non-controlled currents]:

$$w = \left[i_1 i_2\right]^T$$

GSC currents [Controlled currents]:

$$u = \left[i_3 i_4\right]^T$$



In order to establish power sharing, the droop controller for both GSC is equal:

$$K = \begin{bmatrix} K_1 & 0 \\ 0 & K_2 \end{bmatrix} = K_G \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

Case 1: Droop in the AC grid side

The voltage references do not introduce voltage error to the system

Voltage error - GSC nodes

The voltage error is caused by the WF:

WFC currents Non-controlled currents $w \xrightarrow{S(s)G_{yw}(s)} e$ Errors (controlled voltages)

Voltage error - WFC nodes

The voltage error is caused by the WF:

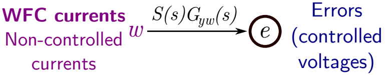
WFC currents Non-controlled currents $w \xrightarrow{G_{zw}(s)+G_{zu}KS(s)G_{yw}(s)} e_z$ **WFC voltages** Non-controlled voltage errors

GSC current - GSC nodes

The GSC current control is caused by the WFC current. Also the GSC current because it is proportional (droop) to the error:

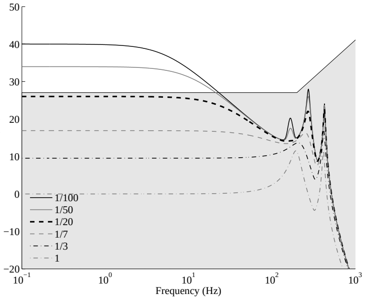
WFC currents Non-controlled currents $w \xrightarrow{KS(s)G_{yw}(s)} u$ **GSC currents** Control action (controlled currents)

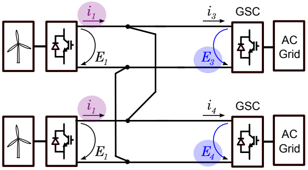
Case 1: Droop in the AC grid side



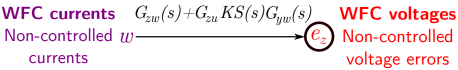
System error - Controlled nodes

- Error caused by the w non controlled (WF currents).
- A constraint is imposed based on the maximum desired error (shadowed area).
- Constraint relaxed in high frequencies (converter bandwith limitation)
- Constants $K \geq \frac{1}{22.5}$ are suitable for the system.



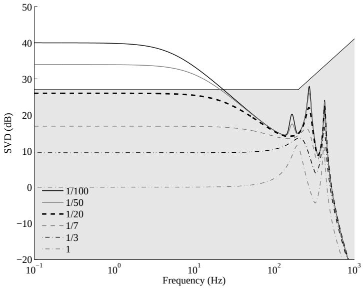


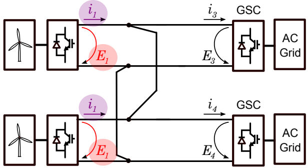
Case 1: Droop in the AC grid side



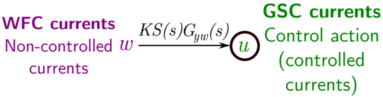
System error - Non controlled nodes

- Error caused by the *w* non controlled inputs (WF currents).
- The frequential response has high frequency peaks that must be taken into account.
- The selected range of constants is $K \geq \frac{1}{20}$



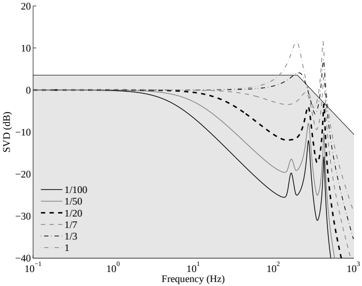


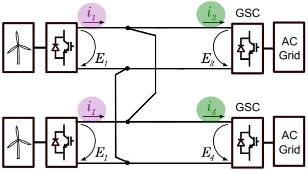
Case 1: Droop in the AC grid side



Control input at the controlled nodes

- The control action is only affected by the pertorbation inputs w.
- A constraint based on the desired current response is established.
- This constraint is strengthened in high frequencies in order not to exceed the bandwith limitation of the converters.
- Constants values of $K_G \leq \frac{1}{20}$ suits the constraint imposed on the singular values representation.

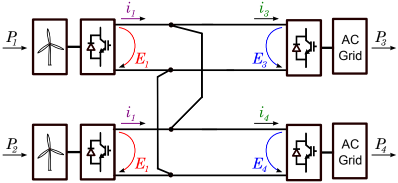


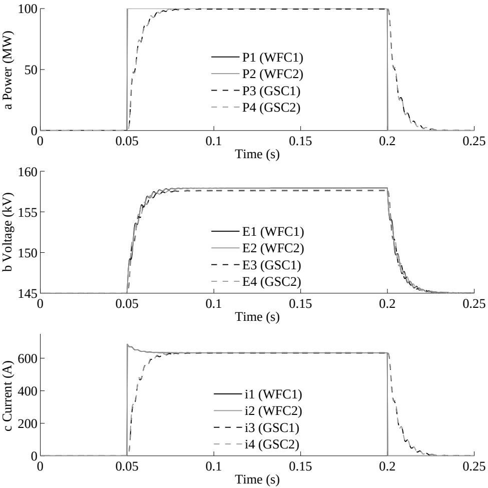


Case 1: Droop in the AC grid side

Four terminal grid simulation

- Power input step change of the two WFC (100 MW).
- K_G is fixed as $\frac{1}{20}$
- Solid lines: WFC
- Dashed lines: GSC





Case 1: Droop WF side

GSC voltages [Non-controlled voltages]

$$z = \left[E_3 E_4\right]^T$$

WFC voltages [Controlled voltages]

$$y = \left[E_1 E_2\right]^T$$

Voltage references:

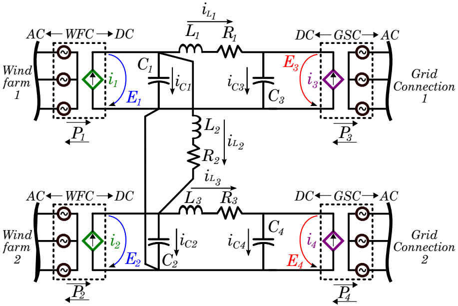
$$E_0 = \left[E_{01} E_{02}\right]^T$$

GSC currents [Non-controlled currents]:

$$w = \left[i_3 i_4\right]^T$$

WFC currents [Controlled currents]:

$$u = \left[i_1 i_2\right]^T$$



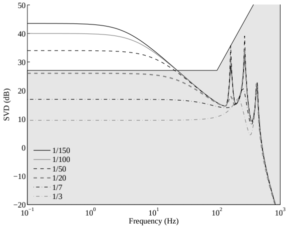
Droop controller parametrization:

$$K = K_G \begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix} = -K_G I_2$$

Case 2: Droop in the WF side

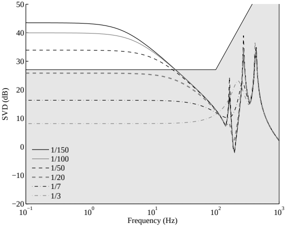
- Follows the same procedure as the previous case.
- Constraints for the singular values are fixed.
- Resonance peaks less damped, larger gain values must be accepted in high frequencies.

GSC currents → WFC Voltage error



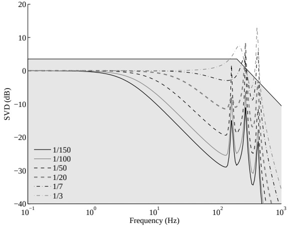
$w(s) \rightarrow e(s)$

GSC currents → GSC Voltage error



$w(s) \rightarrow e_z(s)$

GSC currents → WFC current

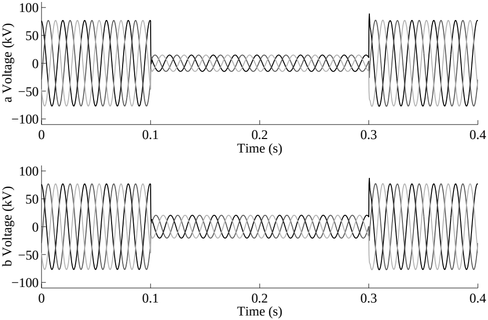


$w(s) \rightarrow u(s)$

Case 2: Droop in the WF side

Voltage sag at both GSC

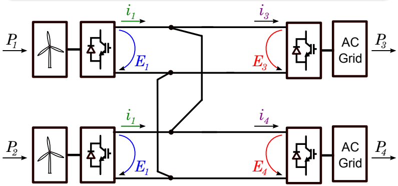
- The parameter K_G is fixed as $\frac{1}{20}$.
- Nominal power input from the two WFVSC converters.
- GSC 1: 90% of voltage reduction
- GSC 2: 80% of voltage reduction

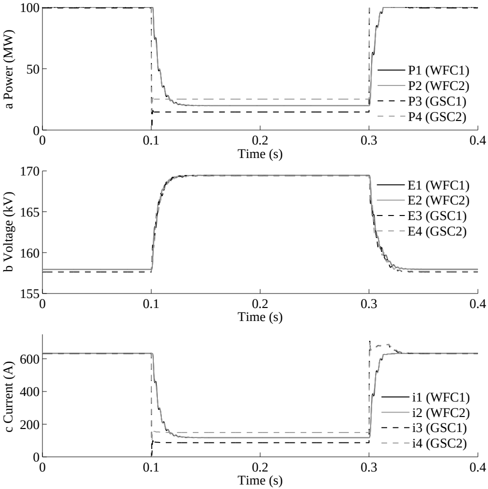


Case 2: Droop in the WF side

Voltage sag at both GSC

- Over 160 kV the WFC starts to control the grid DC bus voltage
- Solid lines: WFC
- Dashed lines: GSC





Thanks!