Control and Stability Analysis of Offshore Meshed HVDC Grids

Modeling HVDC grids as a feedback control system

Ali Bidadfar

October 13, 2017

Denmark Technical University
Wind Energy Department

© PROMOTioN - Progress on Meshed HVDC Offshore Transmission Networks
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691714

Table of contents

Introduction

Specifications of DC grids:

- Low impedance of transmission lines (higher short circuit current)

Specifications of DC grids:

- Low impedance of transmission lines (higher short circuit current)
- Faster dynamics (small time delays play significant role in system dynamic)

Specifications of DC grids:

- Low impedance of transmission lines (higher short circuit current)
- Faster dynamics (small time delays play significant role in system dynamic)
- Lower tolerance to faulty situations

Specifications of DC grids:

- Low impedance of transmission lines (higher short circuit current)
- Faster dynamics (small time delays play significant role in system dynamic)
- Lower tolerance to faulty situations
- Higher and faster interaction between converters

Specifications of DC grids:

- Low impedance of transmission lines (higher short circuit current)
- Faster dynamics (small time delays play significant role in system dynamic)
- Lower tolerance to faulty situations
- Higher and faster interaction between converters
- The grid control systems must satisfy grid code requirements

Specifications of DC grids:

- Low impedance of transmission lines (higher short circuit current)
- Faster dynamics (small time delays play significant role in system dynamic)
- Lower tolerance to faulty situations
- Higher and faster interaction between converters
- The grid control systems must satisfy grid code requirements
- It connects different system operators who may not the same control paradigm

Specifications of DC grids:

- Low impedance of transmission lines (higher short circuit current)
- Faster dynamics (small time delays play significant role in system dynamic)
- Lower tolerance to faulty situations
- Higher and faster interaction between converters
- The grid control systems must satisfy grid code requirements
- It connects different system operators who may not the same control paradigm
- Control paradigm depends on wind farm production

Research Questions Related to DC Grids:

- How DC and AC systems interact with each other?

Research Questions Related to DC Grids:

- How DC and AC systems interact with each other?
- How this interaction is analysed? (quantified and qualified)

Research Questions Related to DC Grids:

- How DC and AC systems interact with each other?
- How this interaction is analysed? (quantified and qualified)
- How droop controllers impact the system stability?

Research Questions Related to DC Grids:

- How DC and AC systems interact with each other?
- How this interaction is analysed? (quantified and qualified)
- How droop controllers impact the system stability?
- Can voltage and frequency droop be implemented on one converter?

Research Questions Related to DC Grids:

- How DC and AC systems interact with each other?
- How this interaction is analysed? (quantified and qualified)
- How droop controllers impact the system stability?
- Can voltage and frequency droop be implemented on one converter?
- Can conventional tools be used for DC grid stability analysis?

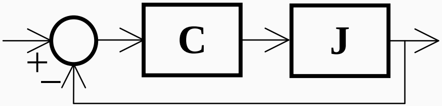
Research Questions Related to DC Grids:

- How DC and AC systems interact with each other?
- How this interaction is analysed? (quantified and qualified)
- How droop controllers impact the system stability?
- Can voltage and frequency droop be implemented on one converter?
- Can conventional tools be used for DC grid stability analysis?
- more possible questions!

Feedback Control System Model and its Benefits

An appropriate model (a tool) to answer the research questions:

Modeling entire system as a linear, time invariant, multi-input multi-output Feedback Control System (FCS)



The FCS model is a basic concept in control engineering!
J and **C** are respectively plant (Jacobian) and controller system model in Laplas domain.

Why FSC model?

- System dynamic can be studied in both time and frequency domain.

Why FSC model?

- System dynamic can be studied in both time and frequency domain.
- Provides more insight into system dynamics.

Why FSC model?

- System dynamic can be studied in both time and frequency domain.
- Provides more insight into system dynamics.
- An appropriate model for controller design (Many controller design methods are based on the open loop transfer function).

Why FSC model?

- System dynamic can be studied in both time and frequency domain.
- Provides more insight into system dynamics.
- An appropriate model for controller design (Many controller design methods are based on the open loop transfer function).
- The Grid Code Requirements can be taken into account when the limits for the system stability and performance are determined.

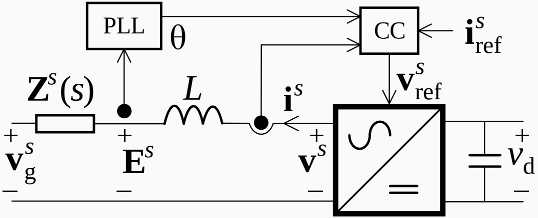
Why FSC model?

- System dynamic can be studied in both time and frequency domain.
- Provides more insight into system dynamics.
- An appropriate model for controller design (Many controller design methods are based on the open loop transfer function).
- The Grid Code Requirements can be taken into account when the limits for the system stability and performance are determined.
- The interaction between ac and dc systems, and also between converters can be quantified and qualified.

Example 1: Stability of Current Control Loop of a Grid Connected VSC

A VSC connected to strong DC and AC grids at both sides.

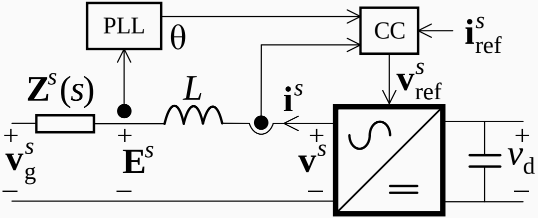
- Does this control loop ever go to instability?



Example 1: Stability of Current Control Loop of a Grid Connected VSC

A VSC connected to strong DC and AC grids at both sides.

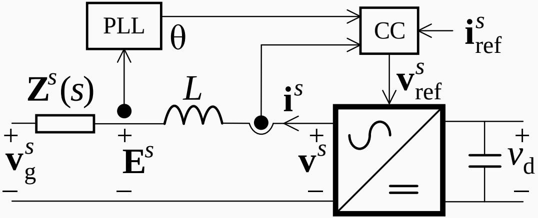
- Does this control loop ever go to instability?
- If yes, what is the cause?



Example 1: Stability of Current Control Loop of a Grid Connected VSC

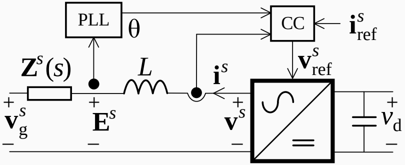
A VSC connected to strong DC and AC grids at both sides.

- Does this control loop ever go to instability?
- If yes, what is the cause?
- And how it can be identified and taken into account in controller design?



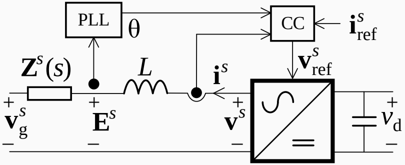
Example 1: Stability of Current Control Loop of a Grid Connected VSC

- System becomes unstable when the controller gain has a large value.



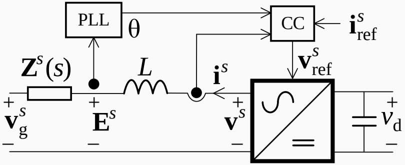
Example 1: Stability of Current Control Loop of a Grid Connected VSC

- System becomes unstable when the controller gain has a large value.
- Transport and sampling delay caused by the PWM process and digital controller sampling/computation can lead to instability [Holmes et al., 2009].



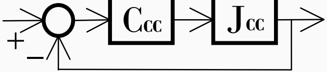
Example 1: Stability of Current Control Loop of a Grid Connected VSC

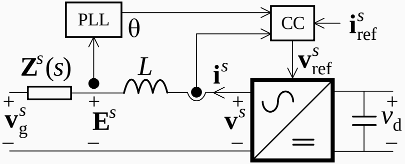
- System becomes unstable when the controller gain has a large value.
- Transport and sampling delay caused by the PWM process and digital controller sampling/computation can lead to instability [Holmes et al., 2009].
- With modal analysis stability and its cause is not identified.



Example 1: Stability of Current Control Loop of a Grid Connected VSC

For stability analysis the frequency response of FCS open loop model is used.

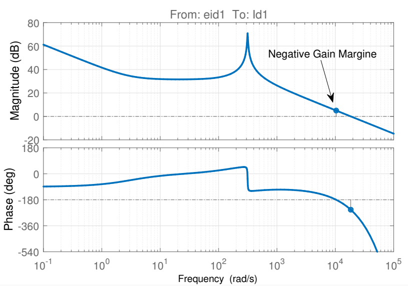


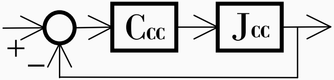


$\mathbf{J}_{CC}$ is the AC system model and $\mathbf{C}_{CC}$ current controller model.

Example 1: Stability of Current Control Loop of a Grid Connected VSC

The frequency response of the system indicates that the system is unstable!

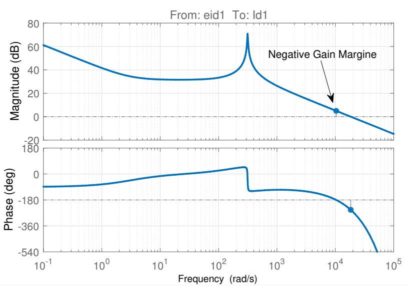


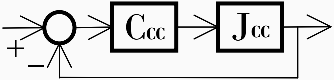


- The negative gain margin in open-loop transfer function indicate the instability.

Example 1: Stability of Current Control Loop of a Grid Connected VSC

The frequency response of the system indicates that the system is unstable!

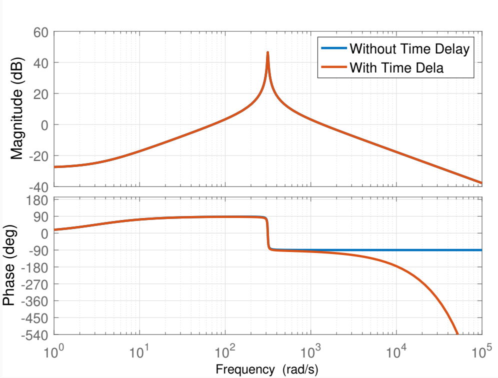


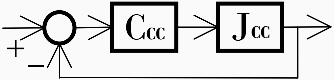


- The negative gain margin in open-loop transfer function indicate the instability.
- How to detect the cause of instability?

Example 1: Stability of Current Control Loop of a Grid Connected VSC

The frequency response of the plant model with and without time delay!

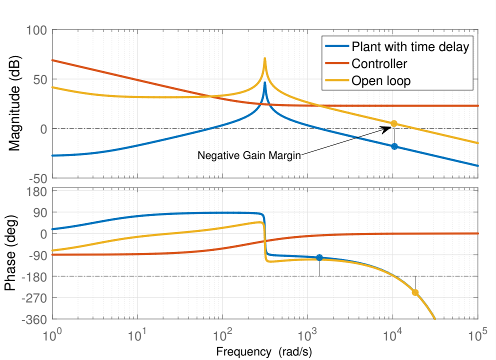


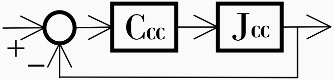


Time delay changes the phase of the plant model, **J**, at high frequency.

Example 1: Stability of Current Control Loop of a Grid Connected VSC

The controller must have low gain at high frequency.

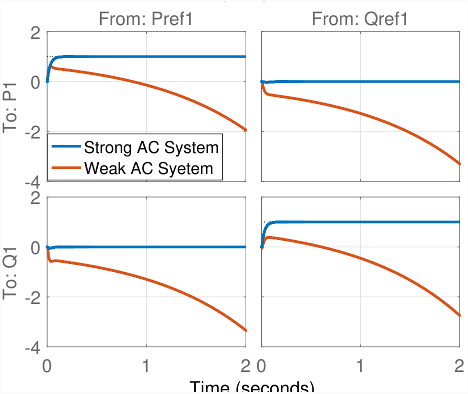


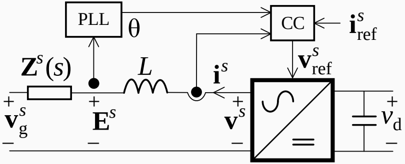


In controller design the time delay must be taken into account!

Example 2: Stability of Power Control Loop of a Weak Grid Connected VSC

A VSC connected to a weak AC grid.

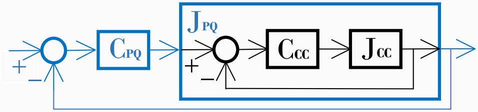


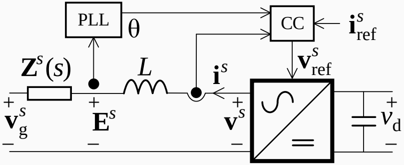


The system is unstable when AC grid is weak!

Example 2: Stability of Power Control Loop of a Weak Grid Connected VSC

The FCS model for power control loop!



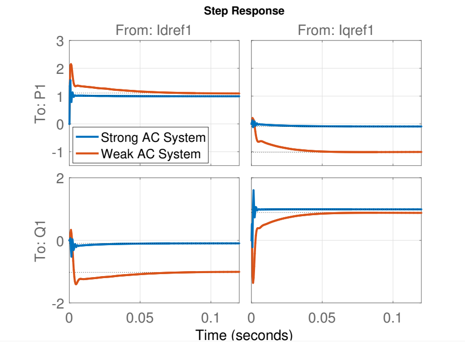


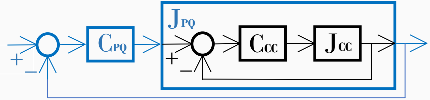
J$_{PQ}$ is the plant model (AC system and current controller model).

C$_{PQ}$ is the power loop controller model (usually a pair of PI controller).

Example 2: Stability of Power Control Loop of a Weak Grid Connected VSC

The accessibility of the plant, $\mathbf{J}_{PQ}$, model help to understand the cause of instability!





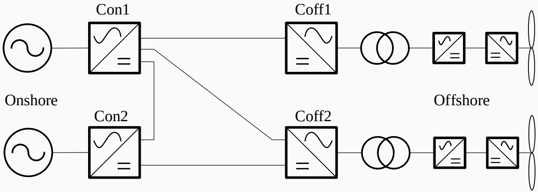
There are severe interactions between P and Q control loops when AC grid is weak.

The plant is ill-condition at low frequencies!

Developing Feedback Control System Model for an HVDC Grid

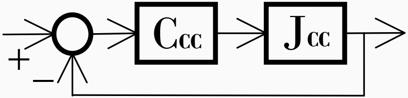
FCS Model of an HVDC Grid:

One of the possible DC grid topologies considered for North Sea



FCS Model of an HVDC Grid:

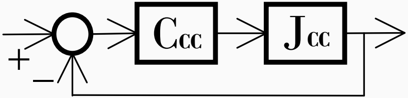
FCS Model for Converters Current Control Loop:



- The model is block-diagonal i.e. DC grid dynamic can be neglected and CC can be design independently for each converter!

FCS Model of an HVDC Grid:

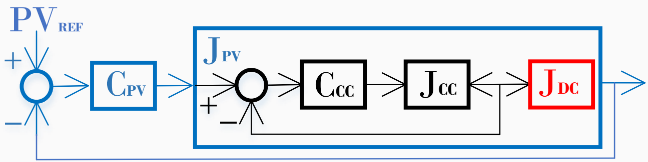
FCS Model for Converters Current Control Loop:



- The model is block-diagonal i.e. DC grid dynamic can be neglected and CC can be design independently for each converter!
- Each AC system is represented by a Thevenin equivalent.

FCS Model of an HVDC Grid:

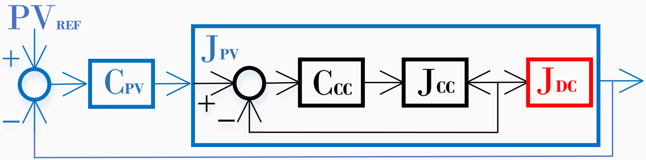
FSC model for Power (Active and Reactive) and Voltage (AC and DC) Contrl



- The DC grid dynamic, $\mathbf{J}_{DC}$, is included in the plant model, $\mathbf{J}_{PV}$.

FCS Model of an HVDC Grid:

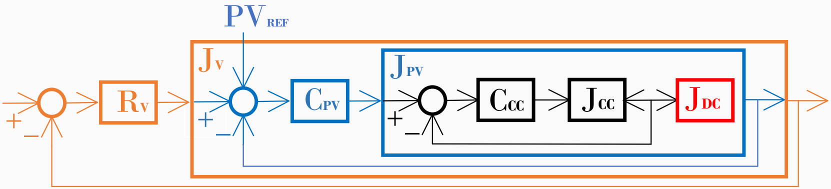
FSC model for Power (Active and Reactive) and Voltage (AC and DC) Contrl



- The DC grid dynamic, $\mathbf{J}_{DC}$, is included in the plant model, $\mathbf{J}_{PV}$.
- Each AC system is represented by a Thevenin equivalent (detailed model can be regarded of a fast dynamic device like FACTS devices is in nearby).

FCS Model of an HVDC Grid:

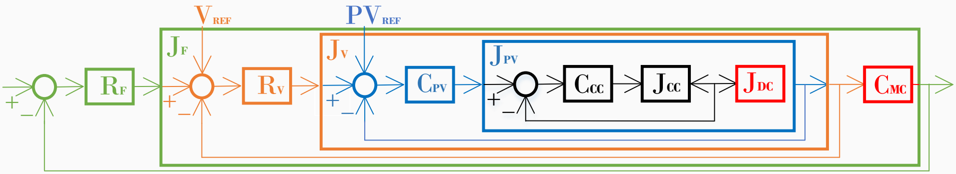
FSC model for Direct Voltage Droop Control



- The direct voltage controller gain, $\mathbf{R}_V$, is the inverse of power-voltage droop!

FCS Model of an HVDC Grid:

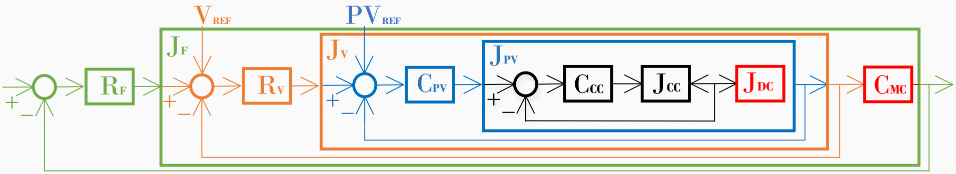
FSC model for Providing Frequency Support to Onshore Grids



- Electromechanical dynamics, $\mathbf{C}_{MC}$, of onshore AC systems are included in the plant model, $\mathbf{J}_F$.

FCS Model of an HVDC Grid:

FSC model for Providing Frequency Support to Onshore Grids



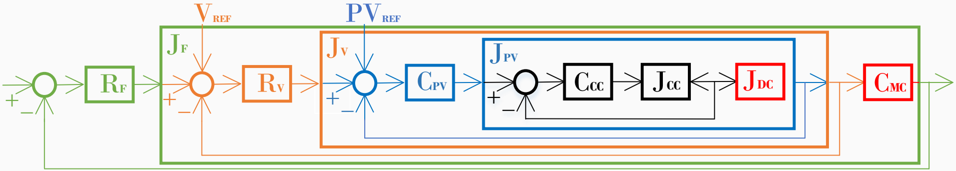
- Electromechanical dynamics, $\mathbf{C}_{MC}$, of onshore AC systems are included in the plant model, $\mathbf{J}_F$.
- There are different schemes of implementing frequency support control (with or without communication, converter pairing, etc.).

FCS Model of an HVDC Grid:

Simplification:

When studying a slow dynamic phenomenon, faster dynamic control loops can be simplified. E.g., in frequency support modeling the converter current control loop can be ignored or simplified by a first order dynamic as:

$$\mathbf{I} = \mathbf{T}_{CC}\mathbf{I}_{ref} \ , \quad \mathbf{T}_{CC} = \frac{\omega_c}{s+\omega_c} \ , \quad \omega_c \approx 1000 \rightarrow 5000 \quad rad/sec$$

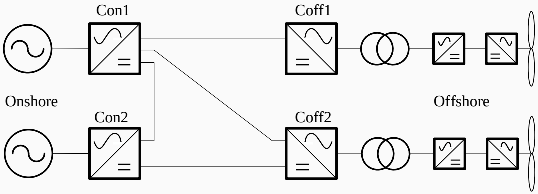


Simulation Results

Simulation Results:

Considerations:

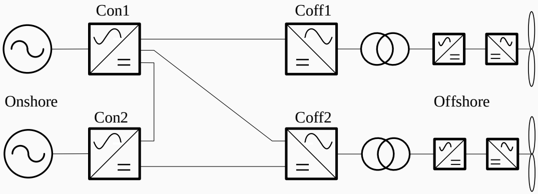
- Dynamics of wind farms are not included (YET) in the FCS model.



Simulation Results:

Considerations:

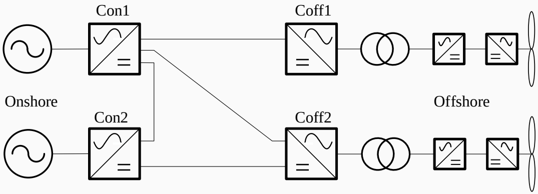
- Dynamics of wind farms are not included (YET) in the FCS model.
- Both of onshore converters participate in direct voltage control.



Simulation Results:

Considerations:

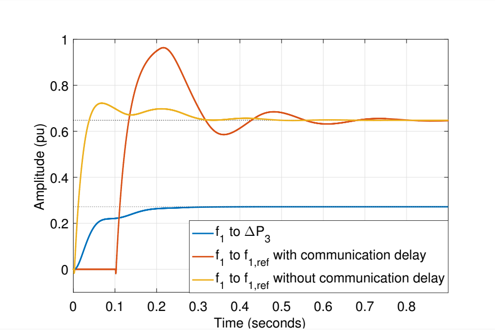
- Dynamics of wind farms are not included (YET) in the FCS model.
- Both of onshore converters participate in direct voltage control.
- Frequency of onshore system one is supported by first offshore wind farm through a communication link.

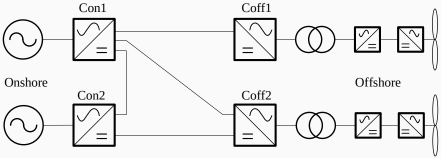


Simulation Results:

Frequency support from offshore one to onshore one

There is 100 ms communication time delay in control loop!

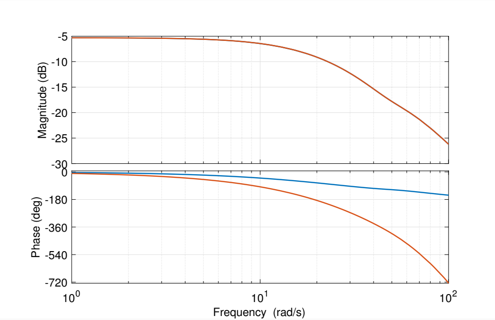


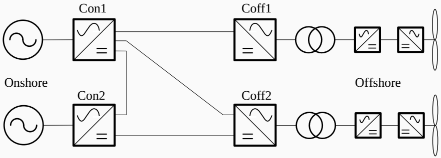


Simulation Results:

Frequency support from offshore one (C3) to onshore one (C1)

There is 100 ms communication time delay in control loop!

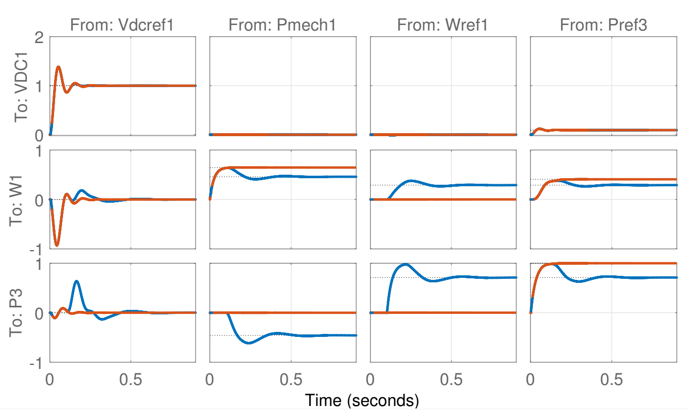




Simulation Results:

Point-to-point connection between Con.1 and Con.3

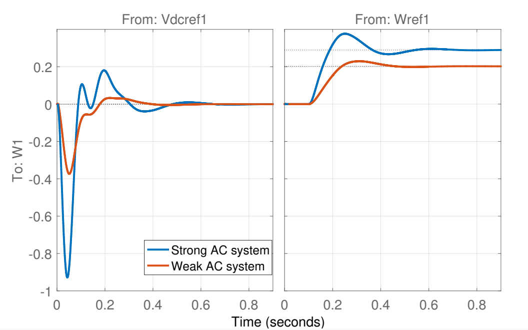
Frequency control creates more interactions between converters. Some overshoots in active power of Con3 must be limited by a proper controllers/limiters.

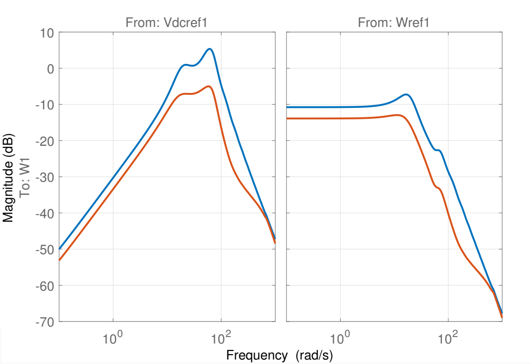


With frequency control; Without frequency control

Simulation Results:

Point-to-point connection between Con.1 and Con.3

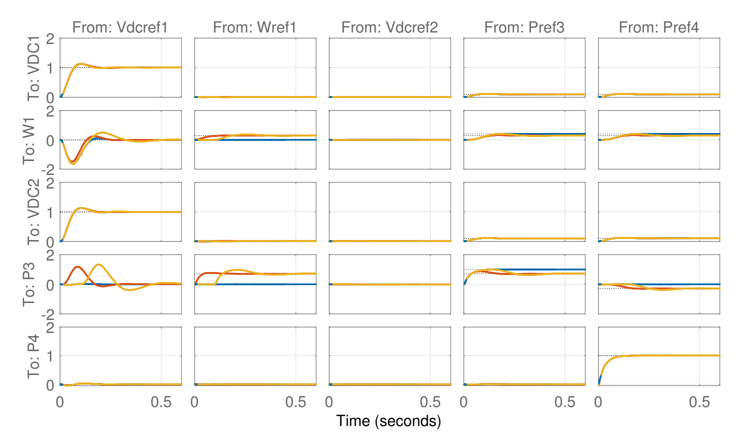




Simulation Results:

Meshed HVDC grid with master-slave control: Con.1 in onshore side controls the direct voltage.

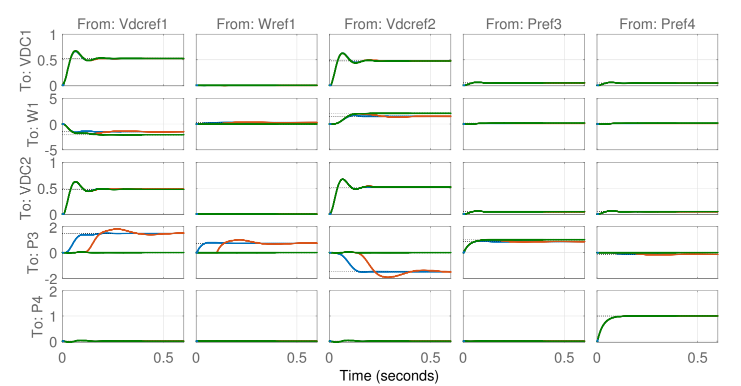
In this control scheme the Con2 and Con4 have not been impacted by frequency control.



Simulation Results:

Meshed HVDC grid with voltage droop control: onshore converters (Con1 and Con2) control the direct voltage.

With communication based frequency control the operation of non-relevant converters is not impacted significantly!



Conclusions

Conclusions:

- FCS model is an appropriate tool for dealing with time delays in fast dynamic systems.

Conclusions:

- FCS model is an appropriate tool for dealing with time delays in fast dynamic systems.
- Interactions between different inputs and outputs can be quantified.

Conclusions:

- FCS model is an appropriate tool for dealing with time delays in fast dynamic systems.
- Interactions between different inputs and outputs can be quantified.
- Frequency and voltage droop controls create complicated interactions between converters

Conclusions:

More inputs to FCS model:

- Wind turbine model

Conclusions:

More inputs to FCS model:

- Wind turbine model
- Communication less method for frequency support

Conclusions:

More inputs to FCS model:

- Wind turbine model
- Communication less method for frequency support
- Offshore wind farm with diode rectifier

Conclusions:

More inputs to FCS model:

- Wind turbine model
- Communication less method for frequency support
- Offshore wind farm with diode rectifier
- Detailed model of AC systems to study power oscillation damping and complicated interactions between AC and DC grids

Questions?

References i

Holmes, D. G., Lipo, T. A., McGrath, B. P., and Kong, W. Y. (2009).
Optimized design of stationary frame three phase ac current regulators.
IEEE Transactions on Power Electronics, 24(11):2417–2426.