VSC-based HVDC Transmission Systems

POWER SYSTEM MODELLING AND CONTROL (EEEN40550)

Prof. Federico Milano

Email: federico.milano@ucd.ie

Tel.: 01 716 1844

Room 157a – Engineering & Materials Science Centre

School of Electrical & Electronic Engineering

University College Dublin

Dublin, Ireland

The material of this lecture was prepared

by Dr. Paul Mc Namara

Outline

- Motivation
- Control p_{ac}, q_{ac}, v_{dc}, v_{ac}
- Frequency control
- Example

Motivation

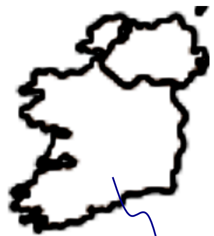
- EU renewable targets
  - For 2020: 20% internally generated
  - For 2030: 27% collectively across Europe

- Electrical Grid Solution
  - Increase wind/solar production
  - Is it this clear cut?

Issues

- Frequency dynamics in isolated AC grid, e.g., Ireland.

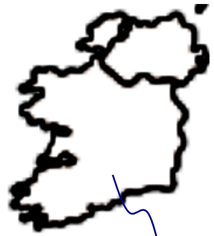
$$\underbrace{\frac{\mathrm{d}\omega}{\mathrm{d}t}}_{\text{Rate of change}} = \frac{1}{M}\Big(\overbrace{p_{\mathrm{m,det}}}^{\text{deterministic power sources}} + \underbrace{p_{\mathrm{m,var}}}_{\text{stochastic power sources}} - \overbrace{p_{\mathrm{e}}}^{\text{loads}} - \underbrace{D(\omega-\omega_s)}_{\text{damping}}\Big)$$



  - $p_{\mathrm{m,det}}$: deterministic power sources. Typically CO_2 **producing**, e.g., coal, oil, gas.
    Highly certain power injection.
  - $p_{\mathrm{m,var}}$: stochastic power sources. Typically CO_2 **free**, e.g., wind, solar.
    Uncertainty associated with power injection.

Issues

$$\underbrace{\frac{d\omega}{dt}}_{\text{Rate of change}} = \frac{1}{M}\Big(\overbrace{p_{\mathrm{m,det}}}^{\text{deterministic power sources}} + \underbrace{p_{\mathrm{m,var}}}_{\text{stochastic power sources}} - \overbrace{p_{\mathrm{e}}}^{\text{loads}} - \underbrace{D(\omega - \omega_s)}_{\text{damping}}\Big)$$

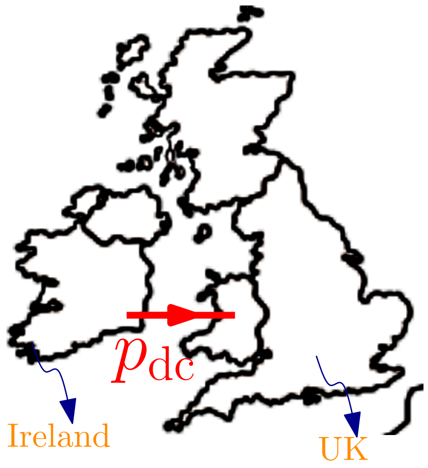


Ireland

- Frequency regulation must be tight.
  - ◇ Max. deviation=± 1 Hz for Ireland
- Increasing $p_{\mathrm{m,var}}$ $\Rightarrow$reduced ability to tightly regulate ω $\Rightarrow$ limit on clean energy penetration.
  - ○ Limit largely dependent on M, the system inertia.

Add HVDC line

$$\underbrace{\frac{\mathrm{d}\omega}{\mathrm{d}t}}_{\text{Rate of change}} = \frac{1}{M}\Big(\overbrace{p_{\mathrm{m,det}}}^{\text{deterministic power sources}} + \underbrace{p_{\mathrm{m,var}}}_{\text{stochastic power sources}} - \overbrace{p_{\mathrm{dc}}}^{\text{exported DC power}} - \overbrace{p_{\mathrm{e}}}^{\text{loads}} - \underbrace{D(\omega - \omega_s)}_{\text{damping}}\Big)$$



- Connect Ireland to UK with HVDC line.
- If too much $p_{\mathrm{m,var}}$, export to UK. i.e. increase p_{dc}
- Also, if too little $p_{\mathrm{m,var}}$, import from UK.

  $\Rightarrow$UK and Ireland can both increase stochastic renewable penetration.

Supergrid

Figure 1: One proposed "Supergrid" (only in planning stages)

- Potential renewable production varies temporally, geographically across Europe.
- HVDC based "Supergrid" planned for Europe.
- Allows continent-wide sharing of renewables.

Note: Supergrid vs large scale storage?

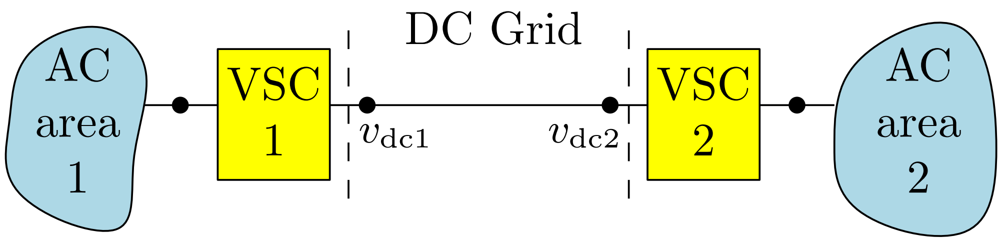
- Large-scale storage may in the future allow excess $p_{\mathrm{m,var}}$ to be stored.
- Serious issues implementing large enough storage facilities. Technology constantly evolving however, e.g., Tesla large scale storage plans.
- Realistic future mix of HVDC & storage still **wide open research question!**
- HVDC posed as way of reaching large scale storage.
  - Norway has massive hydro reserves.
  - By connecting Norway to the Supergrid, could act as a vast battery for the European grid.
  - Sample article: http://spectrum.ieee.org/green-tech/wind/norway-wants-to-be-europes-battery

VSC vs. LCC technology

- Two technologies for implementing HVDC grids: VSCs and Line Commutated Converters (LCCs-see previous HVDC lecture)
- Advantages of VSC
  - Enables bi-directional power flows
  - Independent p_{ac} and q_{ac} control
  - Does not consume reactive power. LCC does.
- Typically most new HVDC lines are VSC.

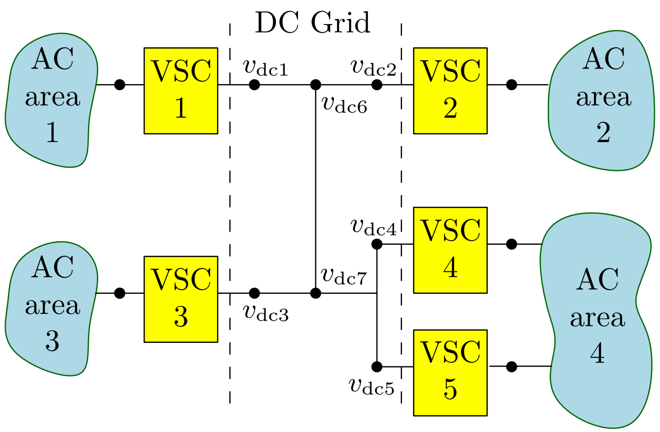
Configurations

- Most existing Back to Back HVDC links are point to point connections, i.e., the DC grid connects on two VSCs together.
  - East-West interconnector, Ireland.



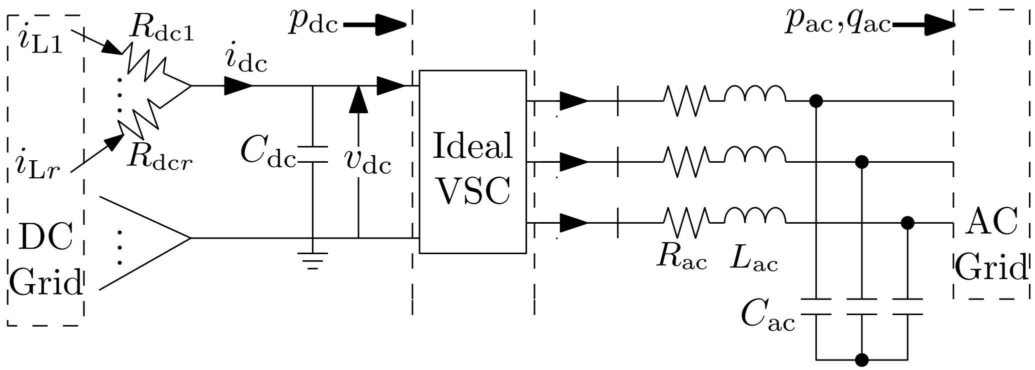
Configurations

- Multi-Terminal HVDC (MTDC) grids are grids where several DC lines connect to one VSC terminal.
- VSC technology enables the construction of flexible meshed MTDC grids. LCC MTDC grids less flexible due to uni-directional flows.
- First built in Nanao, China (2015), Northern European MTDC grid planned, as initial stage of Supergrid.



VSC between AC and DC grids

- Consider a single VSC in a MTDC grid



- Ideal VSC modelled as in FACTs lecture previously.
  - $p_{\mathrm{dc}} = v_{\mathrm{dc}} i_{\mathrm{dc}}$
  - $p_{\mathrm{ac}} = \frac{3}{2}(v_{\mathrm{ac},d} i_{\mathrm{ac,d}} + v_{\mathrm{ac},q} i_{\mathrm{ac,q}})$
  - $q_{\mathrm{ac}} = \frac{3}{2}(-v_{\mathrm{ac},d} i_{\mathrm{ac,q}} + v_{\mathrm{ac},q} i_{\mathrm{ac,d}}) + Q_{c_{\mathrm{ac}}}(t)$
    - $Q_{c_{\mathrm{ac}}}$ is the reactive power corresponding to C_{ac}

DC dynamics

- $C_{\mathrm{dc}} \dfrac{\mathrm{d}}{\mathrm{d}t} v_{\mathrm{dc}} = i_{\mathrm{dc}}$
  - where $i_{\mathrm{dc}} = i_{\mathrm{L1}} + i_{\mathrm{L2}} + \ldots + i_{\mathrm{L}r}$, and the VSC is connected via resistors $R_{\mathrm{dc1}}, \ldots, R_{\mathrm{dc}r}$ to r other DC voltage nodes.
  - Simple DC line models and VSC configurations are used here. More complex models of DC lines and VSC configurations are given in the book: “Multi-terminal Direct-Current Grids: Modelling, Analysis, and Control”, by Chauduri, Chauduri, Majumder, Yazdani, Wiley, 2014 (this is also what the modelling in this lecture is based on).

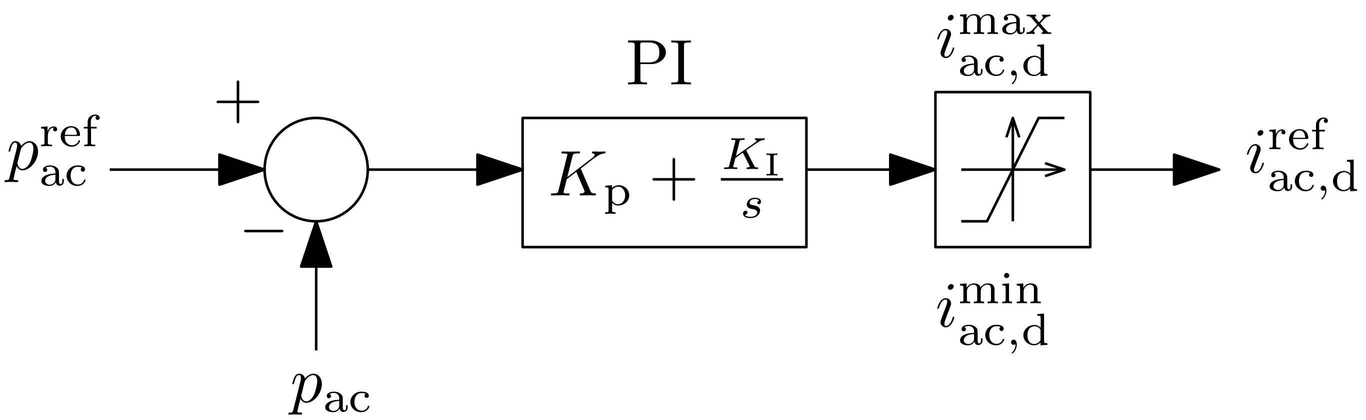
Phase Locked Loop (PLL)

- A PLL ensures that the VSC voltages and currents are synchronised with the system frequency.
- Allows outputs of VSC to be considered in synchronous d-q frame
- When PLL is “locked” into system frequency $v_{\mathrm{ac,q}} = 0$
  $\Rightarrow$powers can now be represented as follows:
  - $p_{\mathrm{ac}} = \frac{3}{2} v_{\mathrm{ac},d} i_{\mathrm{ac,d}}$
  - $q_{\mathrm{ac}} = -\frac{3}{2} v_{\mathrm{ac},d} i_{\mathrm{ac,q}} + \underbrace{\frac{3}{2} C_{\mathrm{ac}} \omega v_{\mathrm{ac},d}^2}_{Q_{c_{\mathrm{ac}}}}$

    $= -\frac{3}{2} v_{\mathrm{ac},d} (i_{\mathrm{ac,q}} - C_{\mathrm{ac}} \omega v_{\mathrm{ac},d})$
- Thus the PLL enables independent control of p_{ac} using $i_{\mathrm{ac,d}}$, and q_{ac} using $i_{\mathrm{ac,q}}$

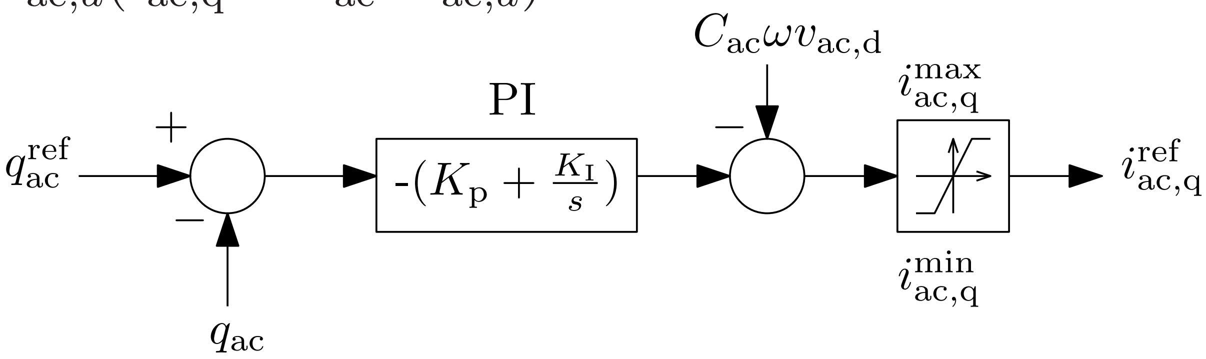
P and Q control

- $p_{\mathrm{ac}} = \frac{3}{2} v_{\mathrm{ac,d}} i_{\mathrm{ac,d}}$; ($v_{\mathrm{ac},d}$ is generally kept near nominal value via voltage regulators)

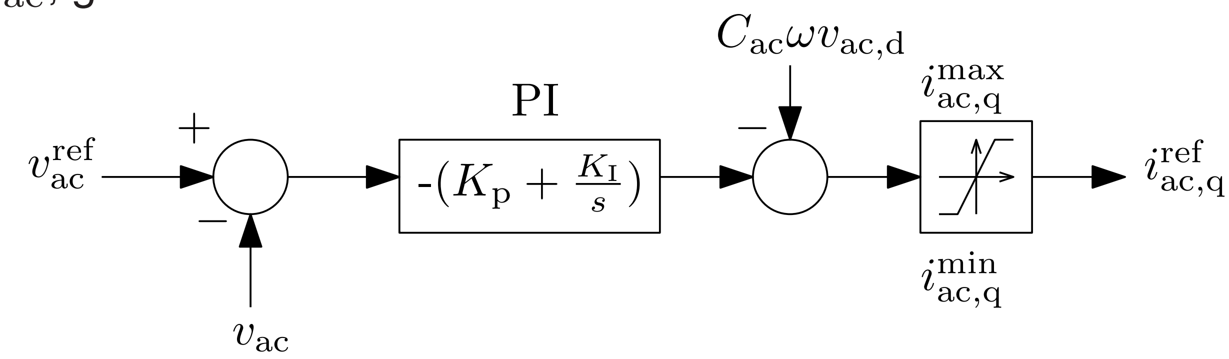


P and Q control

- $q_{\mathrm{ac}} = -\frac{3}{2} v_{\mathrm{ac},d}(i_{\mathrm{ac,q}} - C_{\mathrm{ac}}\omega v_{\mathrm{ac},d})$



- $v_{\mathrm{ac,d}} \propto q_{\mathrm{ac}}$, gives

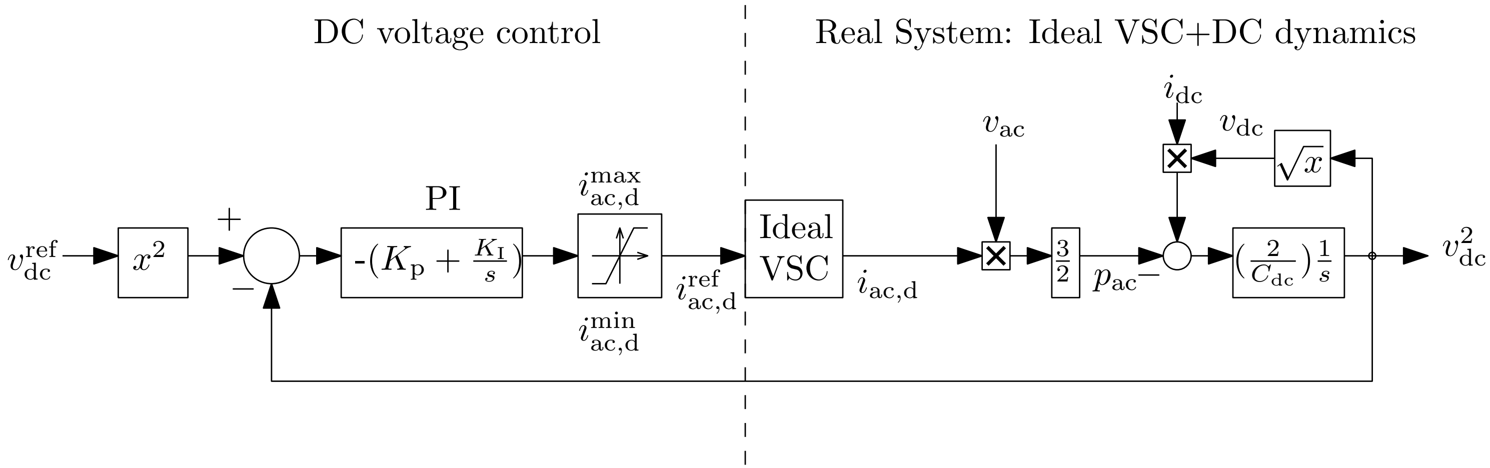


- Note, typically the $-C_{\mathrm{ac}}\omega v_{\mathrm{ac},d}$ part of the controller can be left out.

Control of DC voltage

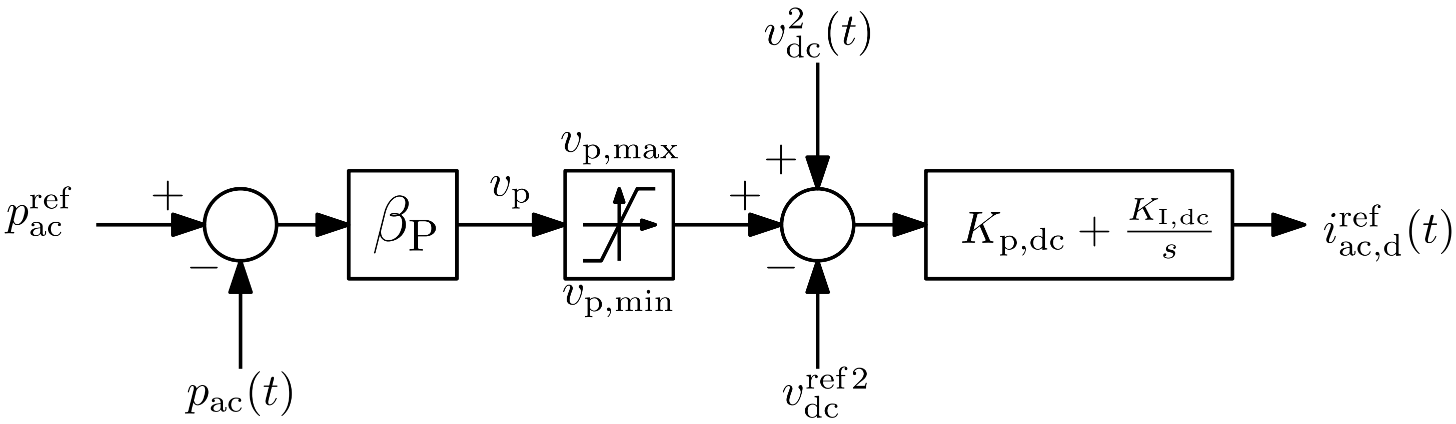
- Assuming minimal losses across VSC: $p_{\mathrm{dc}} = p_{\mathrm{ac}} = \frac{3}{2} v_{\mathrm{ac,d}} i_{\mathrm{ac,d}}$
- Energy in DC Capacitor: $(\frac{C_{\mathrm{dc}}}{2}) \frac{\mathrm{d}v_{\mathrm{dc}}^2}{\mathrm{d}t} = v_{\mathrm{dc}} i_{\mathrm{dc}} - \underbrace{\frac{3}{2} v_{\mathrm{ac,d}} i_{\mathrm{ac,d}}}_{p_{\mathrm{dc}}=p_{\mathrm{ac}}}$
- Chain of influence:

$$v_{\mathrm{dc}}^{\mathrm{ref}} \rightarrow (v_{\mathrm{dc}}^{\mathrm{ref2}} - v_{\mathrm{dc}}^2) \rightarrow i_{\mathrm{ac,d}}^{\mathrm{ref}} \rightarrow i_{\mathrm{ac,d}} \rightarrow \frac{\mathrm{d}v_{\mathrm{dc}}^2}{\mathrm{d}t} \rightarrow v_{\mathrm{dc}}^2 \rightarrow v_{\mathrm{dc}}$$



Combinations

- Use droop gains for regulation trade-offs.
- e.g., $i_{\mathrm{ac,d}}$ can control both p_{ac} and v_{dc}. Dynamic trade-off of both given by:

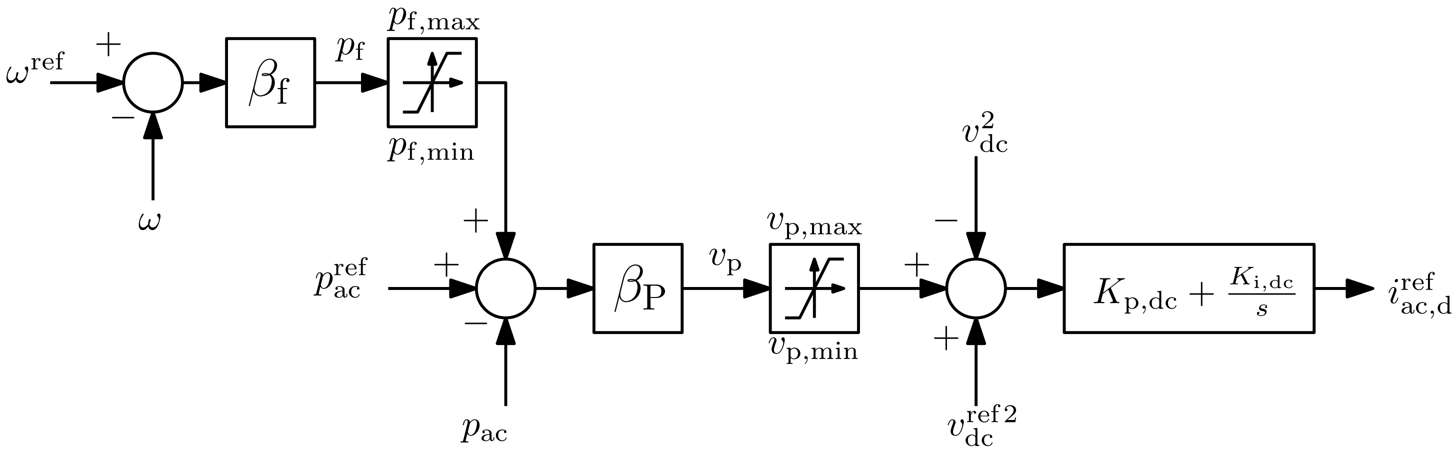


- β_{P} typically a gain. Determines importance of p_{ac} vs. v_{dc} regulation.
- Similar setup possible using $i_{\mathrm{ac,q}}$ for q_{ac} and v_{ac} regulation.

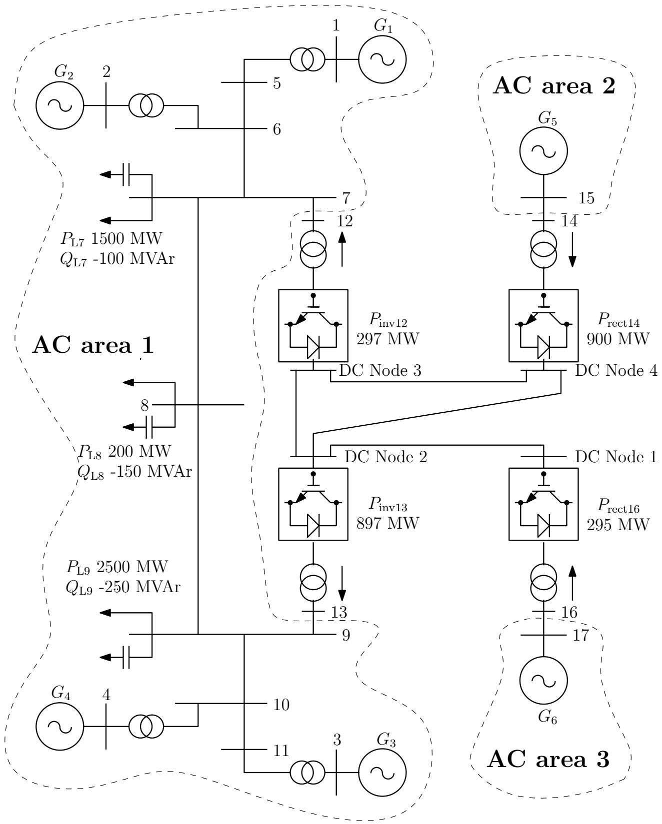
Dynamic frequency regulation

$$\frac{\mathrm{d}\omega}{\mathrm{d}t} = \frac{1}{M}(p_{\mathrm{m,det}} + p_{\mathrm{m,var}} - p_{\mathrm{dc}} - p_{\mathrm{e}} - D(\omega - \omega_s))$$

- System inertia M is provided by rotors (on generators, flywheels, etc).
- As DC interconnections displace machines with that provide inertia, system becomes more prone to large frequency swings.
- Desirable to emulate frequency response in DC power.
- Augment $i_{\mathrm{ac,d}}$ power control to respond to frequency deviations:

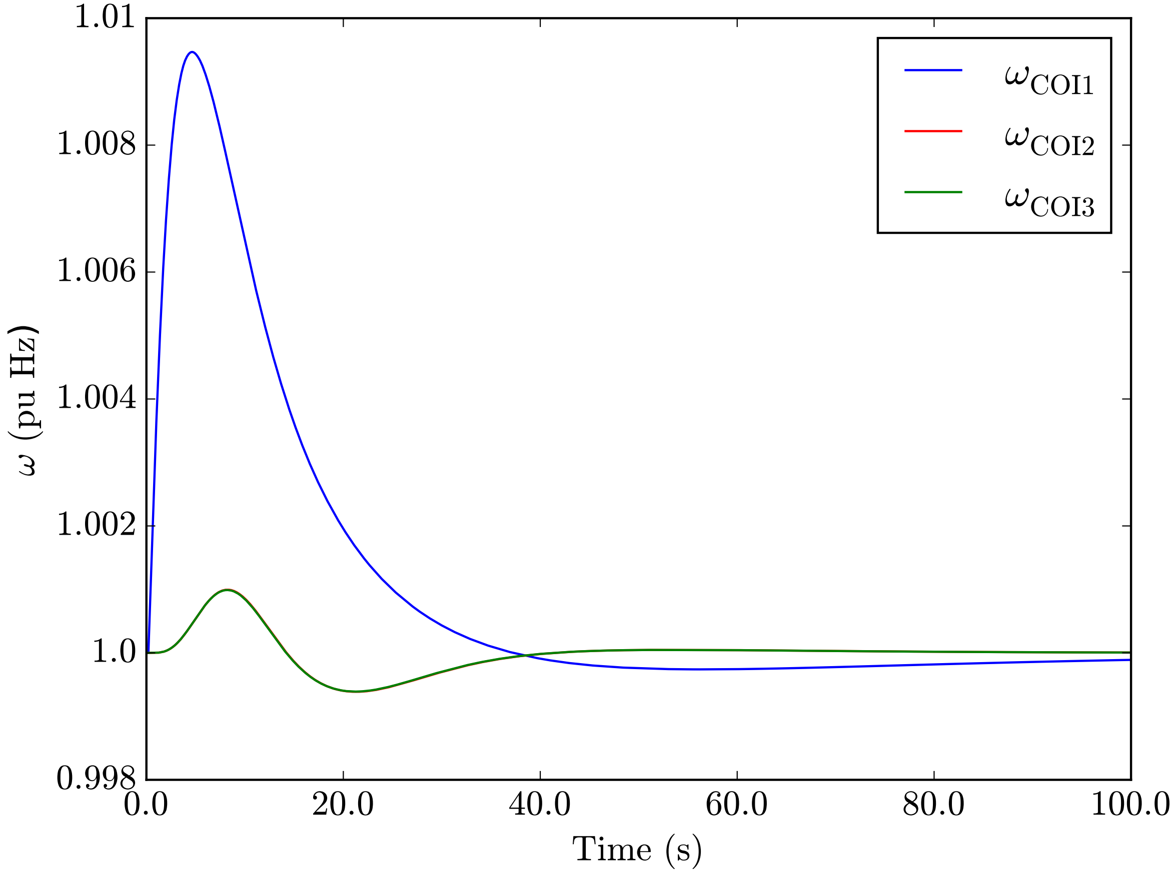


Dynamic frequency regulation example

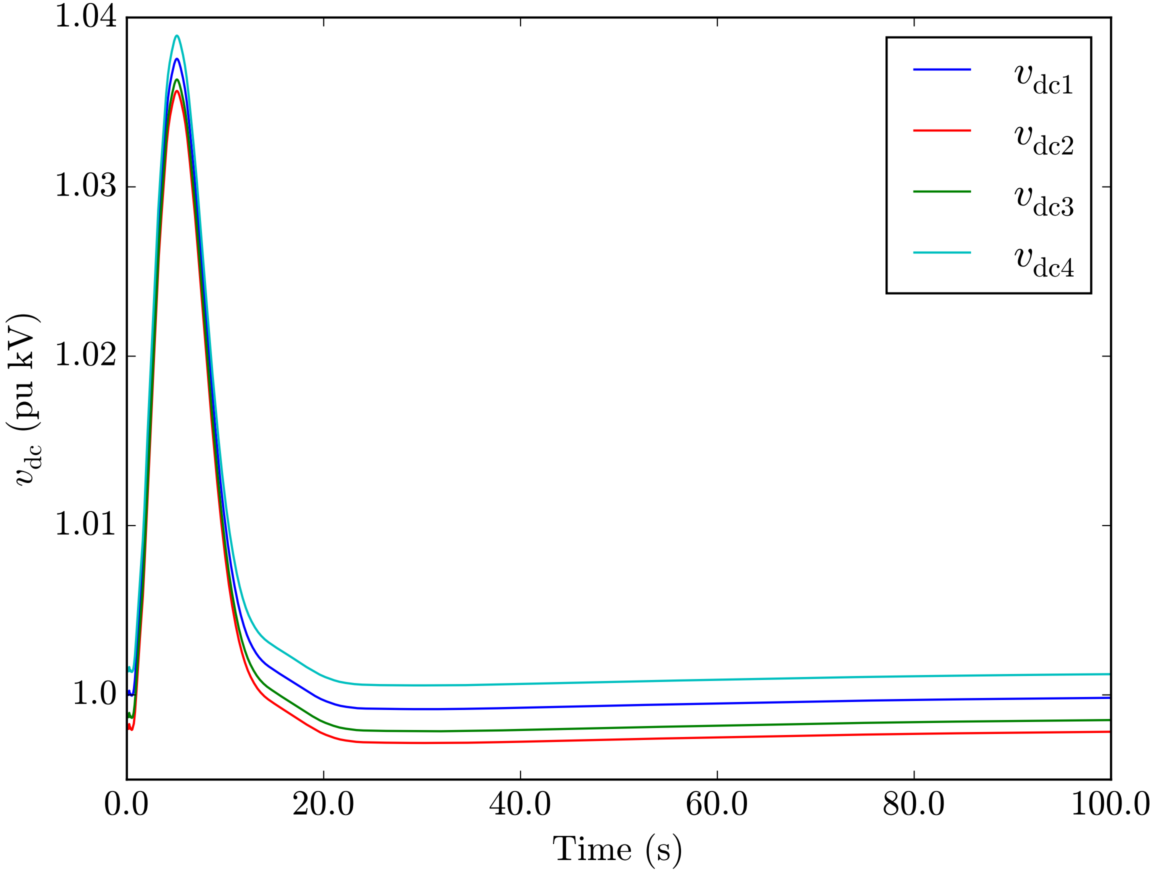


- Consider loss of load 8.

Dynamic frequency regulation example: Frequency



Dynamic frequency regulation example: DC voltages



Dynamic frequency regulation example: DC power deviations