AC versus DC networks – Control and Stability through Modelling

1. DC-Verteilnetztagung – 11th to 12th April 2024

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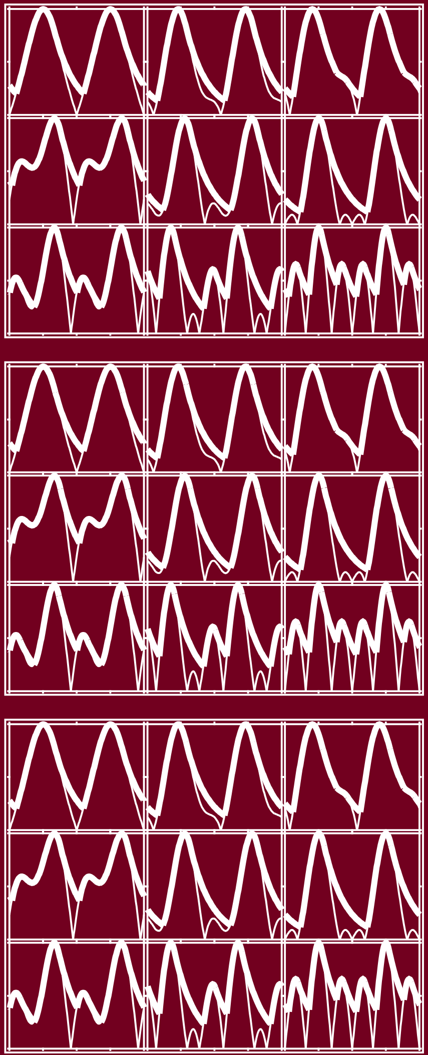
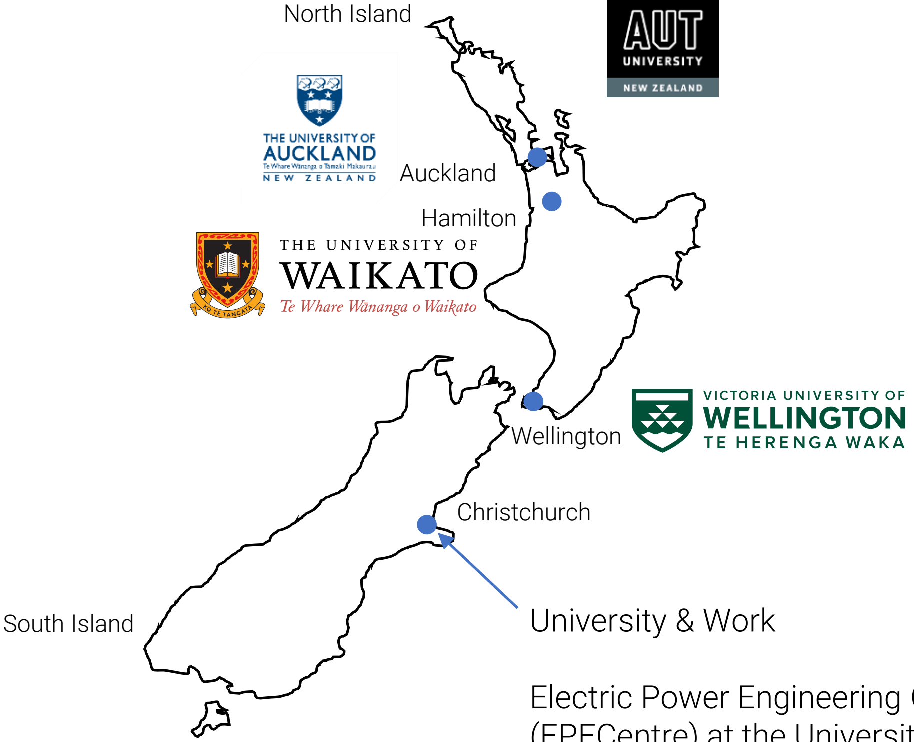


About myself and FAN



University & Work

Electric Power Engineering Centre (EPECentre) at the University of Canterbury

- Pathways for hybrid AC-DC Transmission and Distribution
- Future looking, solve technological challenges to develop the power system of 2050.

Motivation for comparing AC vs DC

- How does it change from AC to DC
    - Power balancing in AC systems is achieved by opening and closing valves.
    - Power imbalances are can be temporarily sustained by the stored kinetic energy in generator inertia.
    - Power flow is not closely coupled to AC voltage magnitude.
    - Power balancing is distributed amongst multiple generators from a common control input of grid frequency for AC systems.

Are DC networks possible?

- Are large DC grids even possible from a control and stability viewpoint?
- What are the principles for designing control systems for DC systems?
- Are DC systems readily expandable?

Outline

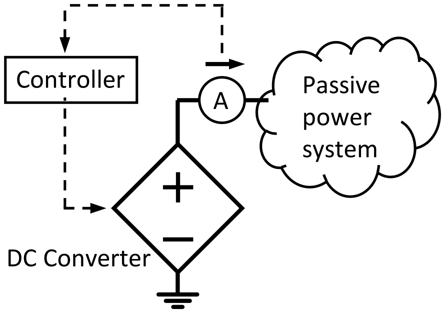
1. Modelling – What is the level of detail required?

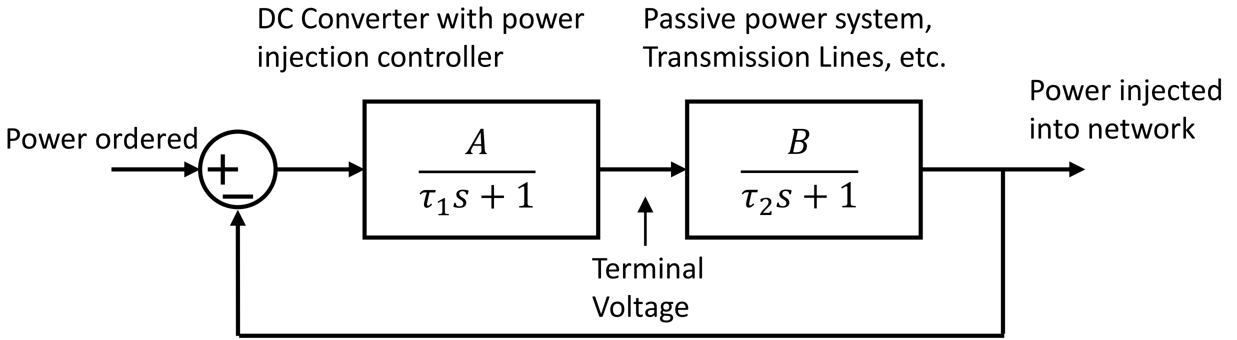
2. Types of Stability – What does stable operation look like?

3. Control – How are system inputs controlled to get the desired output?

4. Stability Analysis – What tools are available to understand system interactions?

Modelling – Is the Network Static or Dynamic?





DC Converter with power injection controller

Passive power system, Transmission Lines, etc.

Power ordered

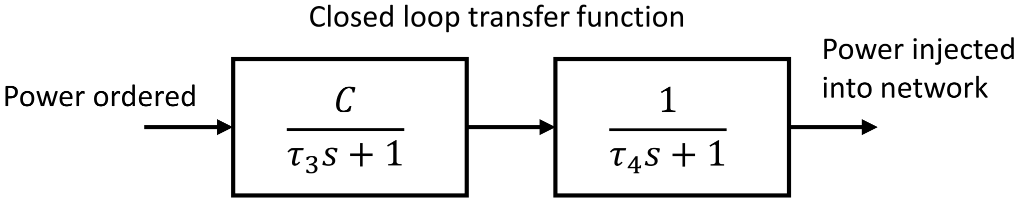
Power injected into network

$\frac{A}{\tau_1 s + 1}$

$\frac{B}{\tau_2 s + 1}$

Terminal Voltage

$$C = \frac{AB}{1 + AB}$$ Closed Loop DC gain



Closed loop transfer function

Power ordered

$\frac{C}{\tau_3 s + 1}$

$\frac{1}{\tau_4 s + 1}$

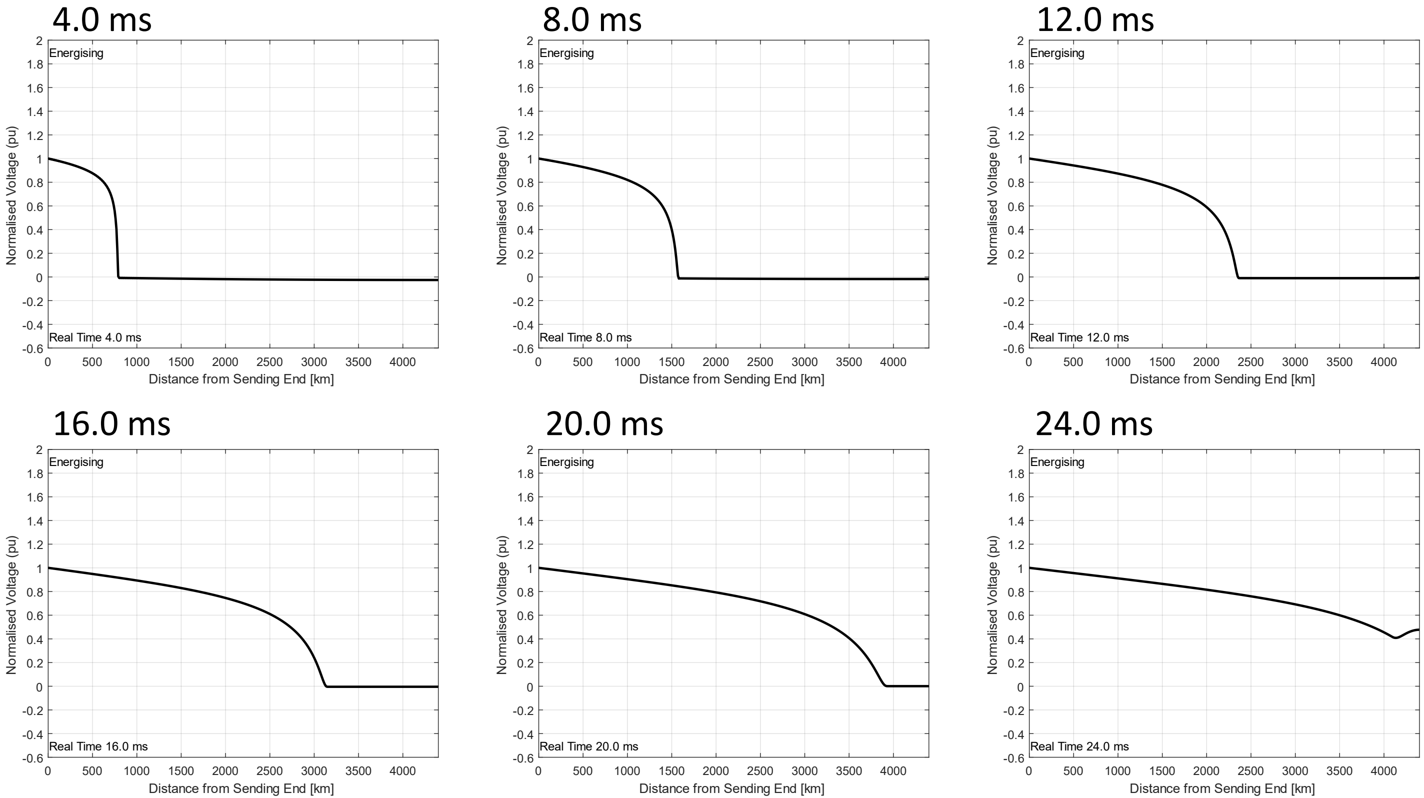
Power injected into network

Assuming $\tau_1 \gg \tau_2$ and $\frac{\tau_2}{\tau_1} \ll \frac{1}{4(1+AB)}$

Then $\tau_3 \approx \frac{\tau_1}{1+AB}$ and $\tau_4 \approx \tau_2$

Transmission Line Modelling

Energisation of 4,400 km HVDC cable.


Cable Voltage

4.0 ms

8.0 ms

12.0 ms

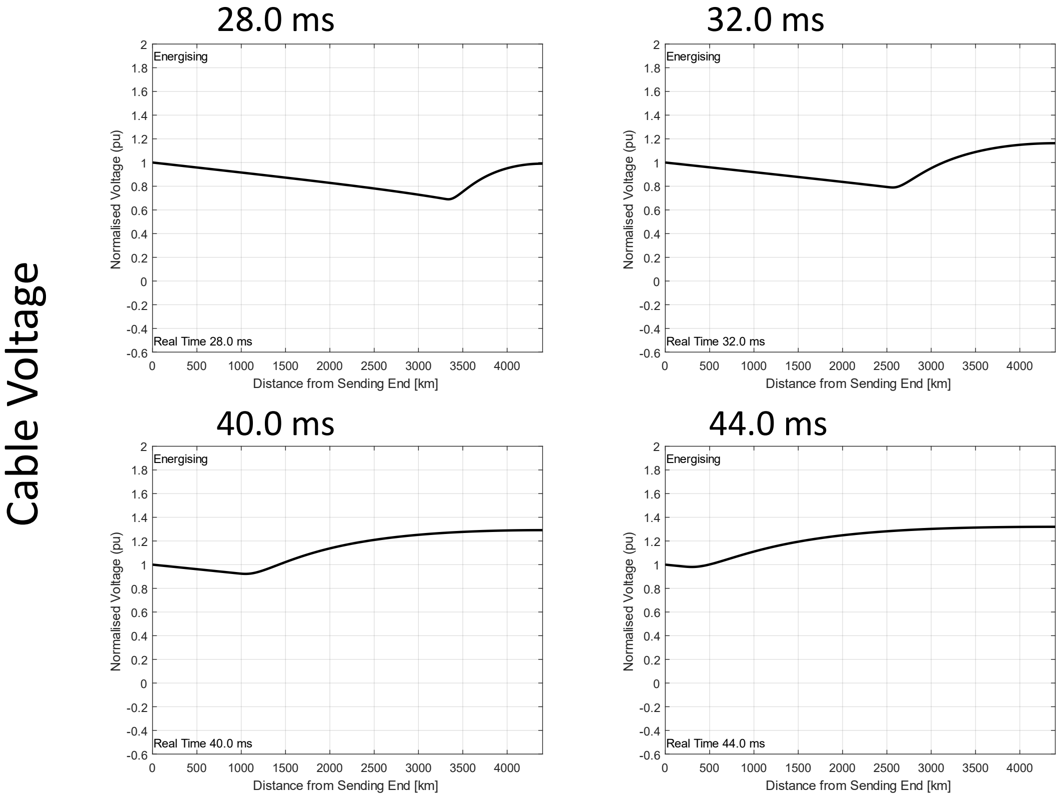
16.0 ms

20.0 ms

24.0 ms

Transmission Line Modelling

Energisation of 4,400 km HVDC cable.



28.0 ms

32.0 ms

36.0 ms

40.0 ms

44.0 ms

The time for the transmission line to settle is dependent on

- Length of transmission line
- Propagation speed
- Attenuation

Modelling Differences between AC and DC

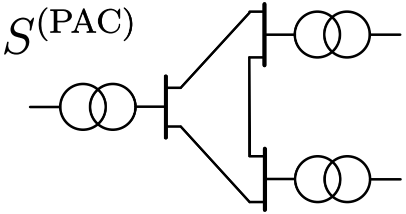
Input variables, e.g. current injection

$$\left.\begin{aligned}\dot{\boldsymbol{x}} &= \boldsymbol{f}(\boldsymbol{x},\boldsymbol{w},\boldsymbol{u})\\ 0 &= \boldsymbol{g}(\boldsymbol{x},\boldsymbol{w},\boldsymbol{u})\\ \boldsymbol{y} &= \boldsymbol{h}(\boldsymbol{x},\boldsymbol{w},\boldsymbol{u})\end{aligned}\right\}\ \text{State model } S$$

Output variables, e.g. terminal voltage

Passive AC System

$S^{(\mathrm{PAC})}$

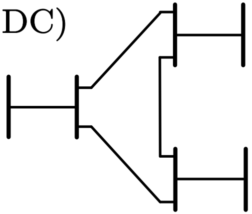


$$S^{(\mathrm{PAC})}\ \begin{cases} 0 = \boldsymbol{g}(\boldsymbol{w},\boldsymbol{u})\\ \boldsymbol{y} = \boldsymbol{h}(\boldsymbol{w},\boldsymbol{u})\end{cases}$$

Algebraic

Passive DC System

$S^{(\mathrm{PDC})}$



$$S^{(\mathrm{PDC})}\ \begin{cases} \dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{x},\boldsymbol{u})\\ \boldsymbol{y} = \boldsymbol{h}(\boldsymbol{x},\boldsymbol{u})\end{cases}$$

Differential

Types of Stability

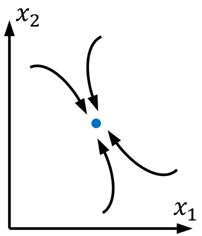
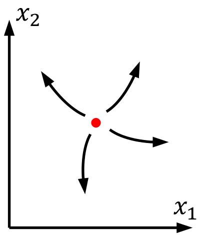
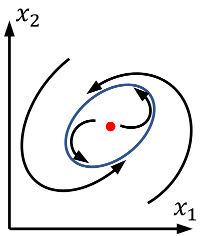
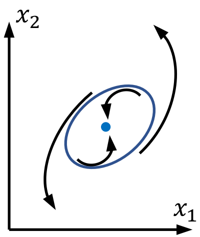
Consider a simple two variable dynamic system

$$\dot{x}_1 = f_1(x_1, x_2)$$
$$\dot{x}_2 = f_2(x_1, x_2)$$

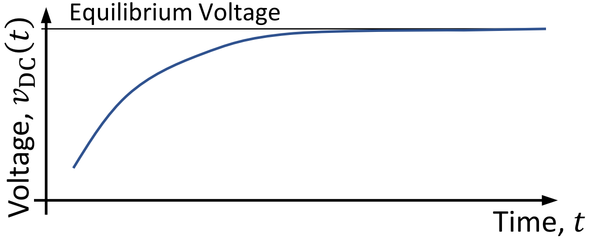
For example, Capacitor Voltage or Inductor Current

Equilibrium points are solutions to

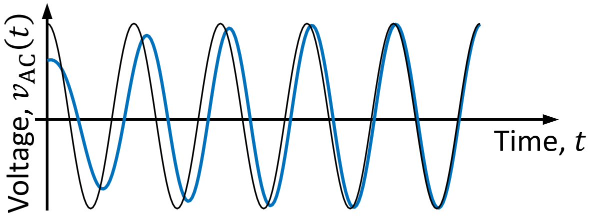
$$0 = f_1(x_1, x_2)$$
$$0 = f_2(x_1, x_2)$$

	Stable	Unstable
Equilibrium Points		
Limit Cycles		
Chaotic	For example Lorenz Attractor	

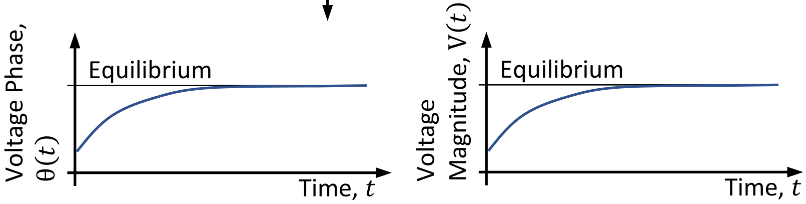
For DC systems



For AC systems



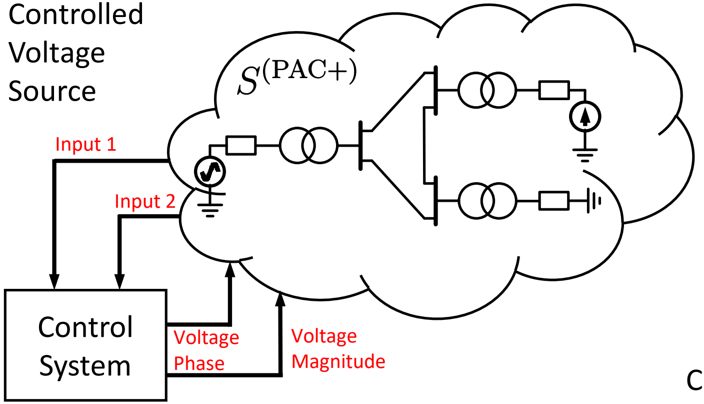
Conversion



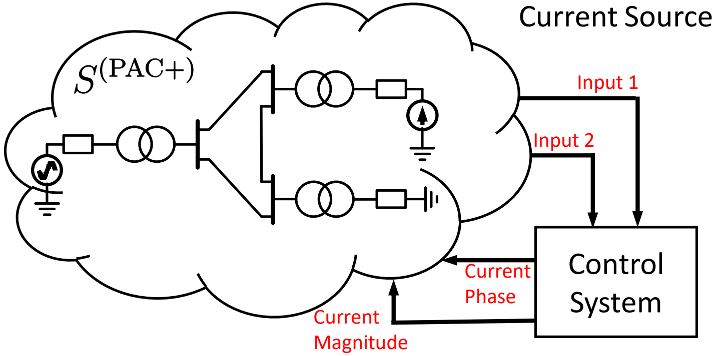
Control Principles for Extended State Models

AC Systems – Two Input and Two Outputs

Controlled Voltage Source

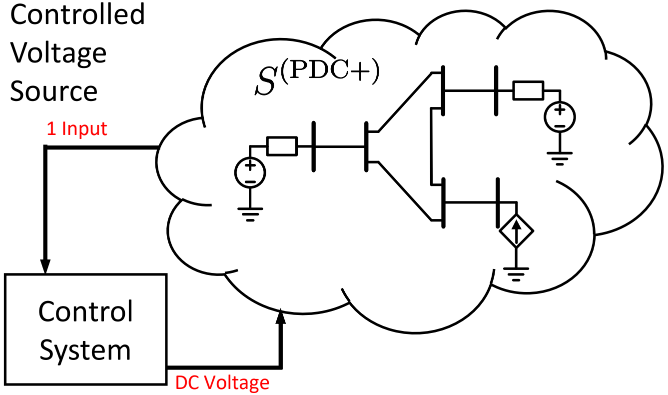


Controlled Current Source

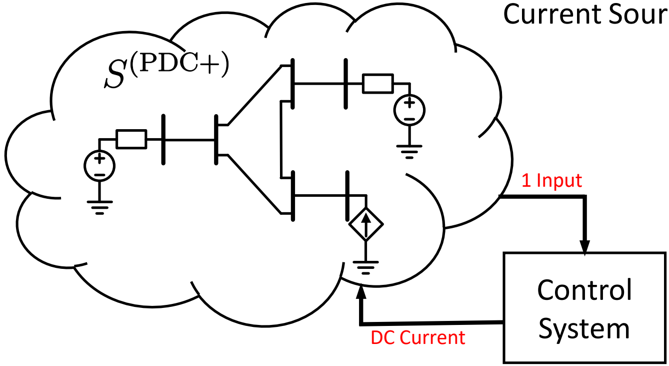


DC Systems – One Input and One Output

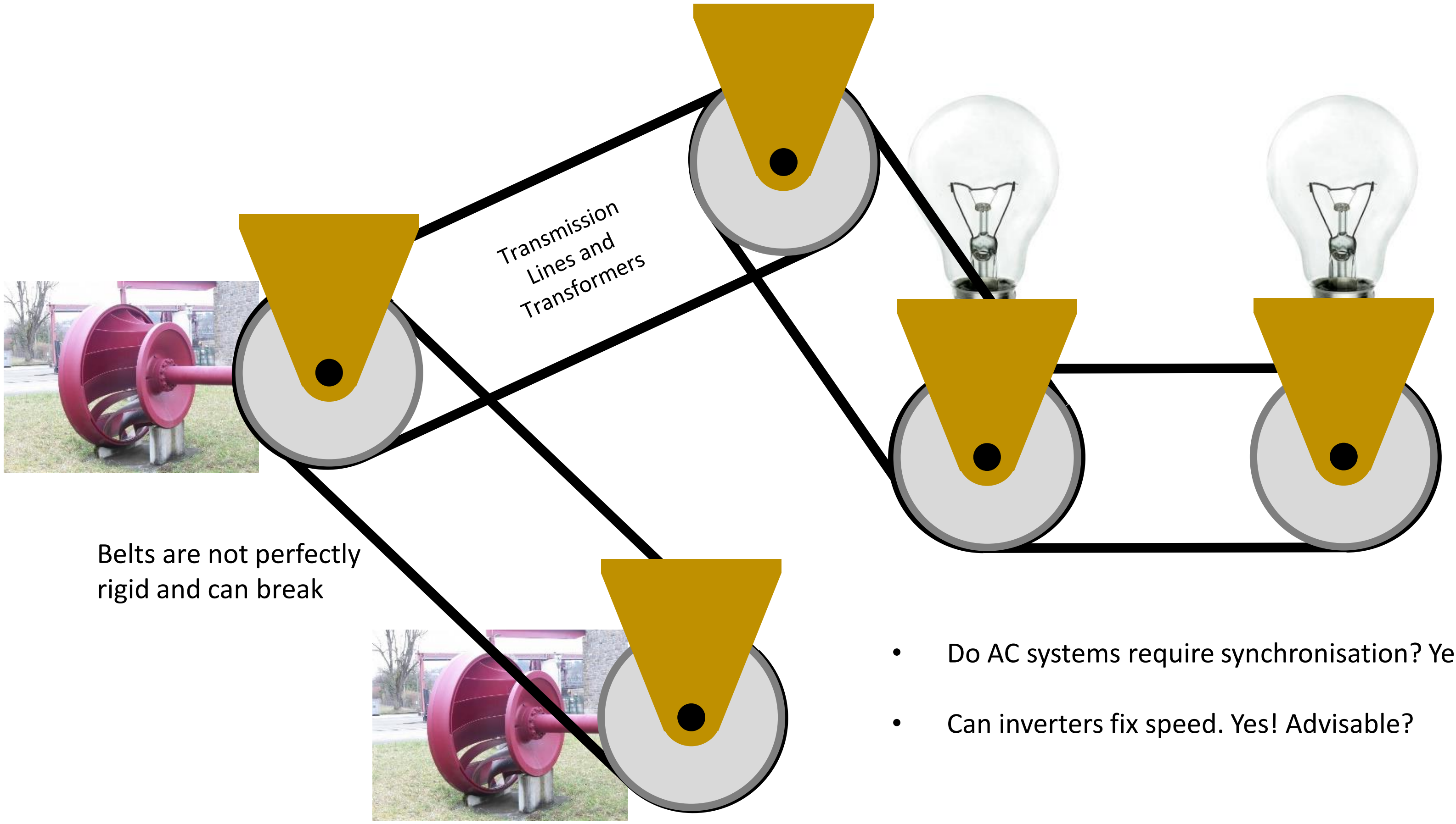
Controlled Voltage Source



Controlled Current Source



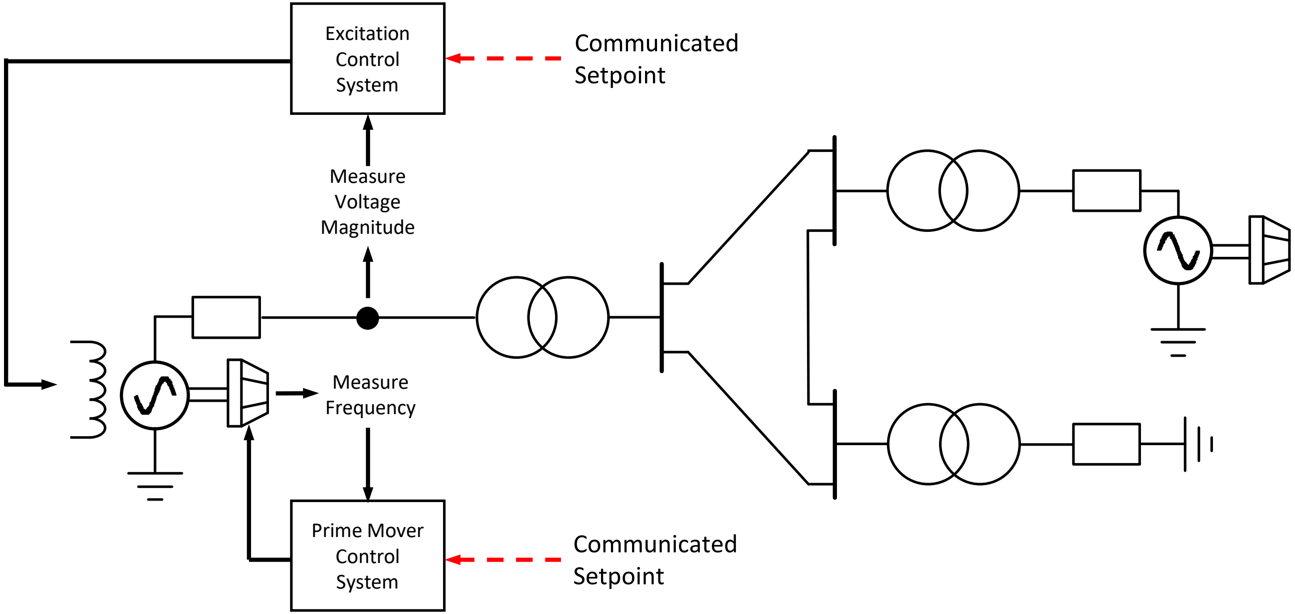
Synchronisation – AC Systems Only



Belts are not perfectly rigid and can break

- Do AC systems require synchronisation? Yes!
- Can inverters fix speed. Yes! Advisable?

Control of AC Systems with Synchronous Generators

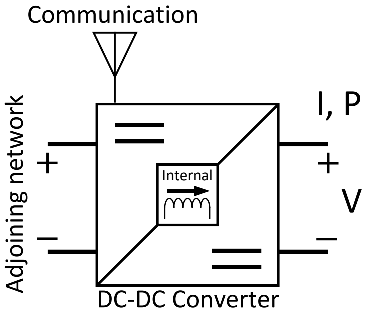


Approaches to Controlling DC Converters

First Select Static Targets

Option	Relationship
1.	Uncontrolled – Load Characteristics
2.	Constant V
3.	Constant I
4.	Constant P
5.	Droop P and V
6.	Droop I and V
7.	Droop P, I and V
8.	+ Deadbands and Control Limits
9.	Nonlinear f(V, I, P)=0
10.	+ Internal state variables + Adjoining network variables
11.	+ Externally communicated setpoints

1. Cannot predetermine all power injected and exported from a network.
2. Voltage has to be predetermined at least one location.



V = Voltage, I = Current, P = Power

Second Determine Dynamic Characteristics

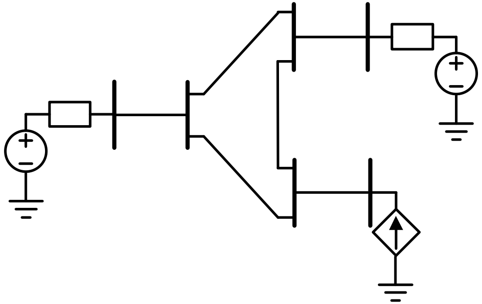
Performance vs Stability vs Cost

For example a Proportional Integral Controller, but many options are possible.

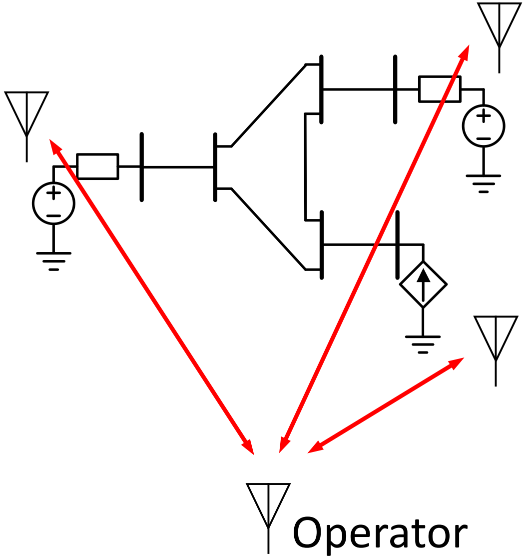
Voltage and Power Management – Option 11

How secure is each configuration to contingencies in the electrical and communications networks?

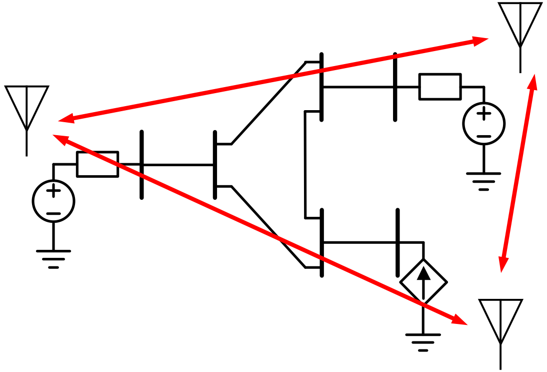
Autonomous



Centralised



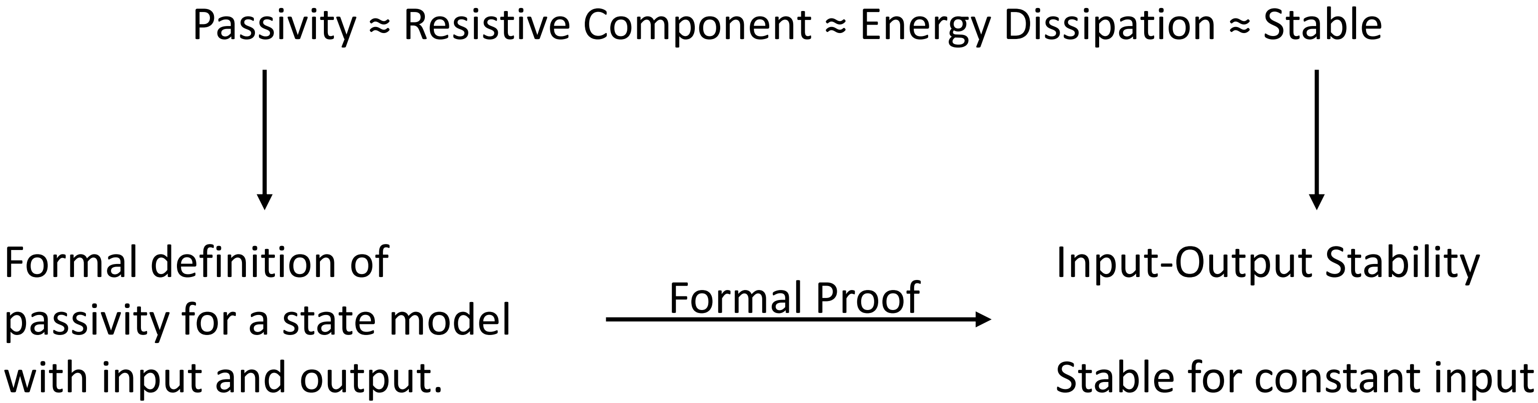
Decentralised



Stability Analysis

- Small Signal Stability – Lyapunov’s Indirect Method
- Time Domain Simulation
- Impedance Analysis – Nyquist Stability Criteria + Related Methods
- Passivity Analysis

Passivity Analysis



Passivity ≈ Resistive Component ≈ Energy Dissipation ≈ Stable

Formal definition of passivity for a state model with input and output.

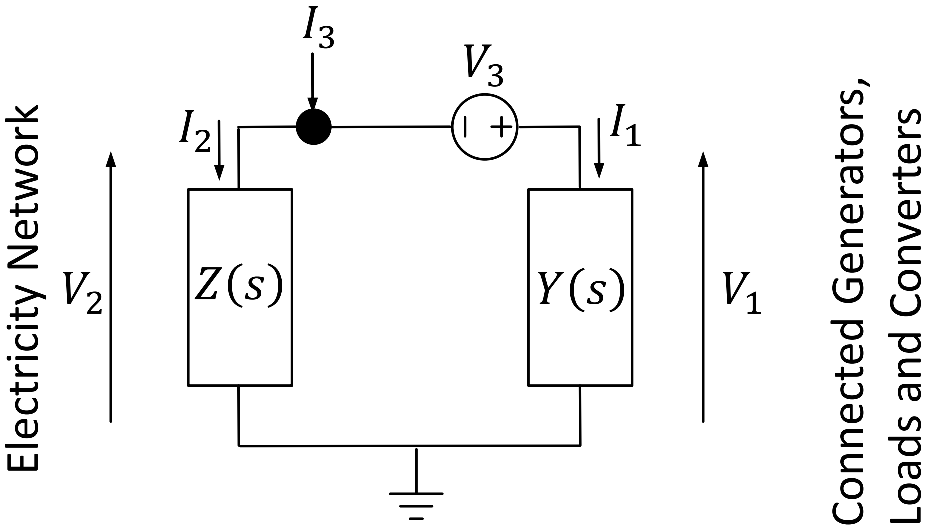
Formal Proof

Input-Output Stability

Stable for constant input

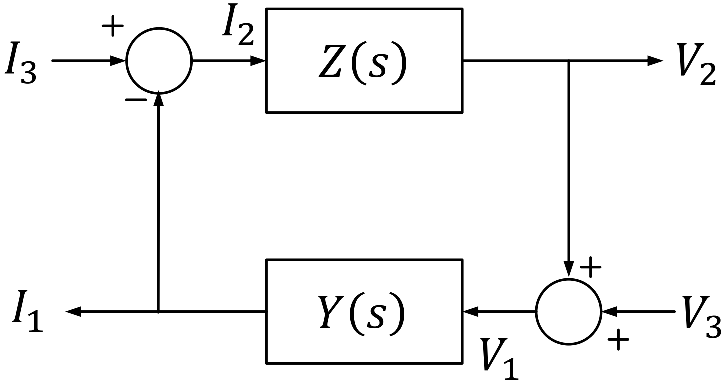
Usefulness of Passivity Analysis - Modularity

Electrical Diagram



Control Diagram

Electricity Network



Connected Generators,
Loads and Converters

If $Z(s)$ and $Y(s)$ are passive, the system from input $\begin{bmatrix} I_3 \\ V_3 \end{bmatrix}$ to $\begin{bmatrix} V_2 \\ I_1 \end{bmatrix}$ is also passive

AC versus DC Summary

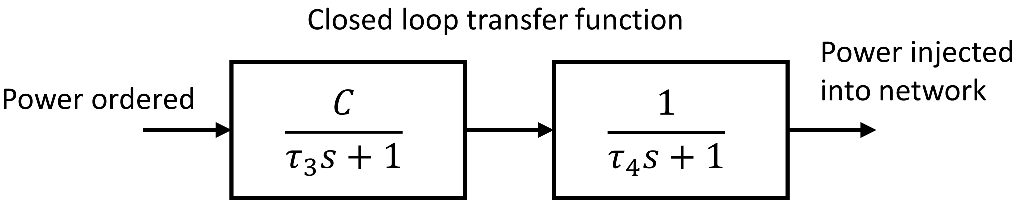
- How does it change from AC to DC
  - Power balancing in AC systems is achieved by opening and closing valves. Not necessary for DC systems, and converters add further flexibility.
  - Power imbalances are can be temporarily sustained by the stored kinetic energy in generator inertia. DC systems require significant energy stores for contingencies.
  - Power flow is not closely coupled to AC voltage magnitude. Power transfer in DC system is created by a DC voltage difference.
  - Power balancing is distributed amongst multiple generators from a common control input of grid frequency for AC systems. Coordinated response of converters in DC systems relies on local DC voltage measurement and communication.

Conclusion

- DC and AC systems have a lot of differences
- Common objective, power transfer with voltage close to nominal
- There are promising tools for analysis

Danke

Poles of Simple Feedback System



Closed loop transfer function

Power ordered

$$\frac{C}{\tau_3 s + 1} \qquad \frac{1}{\tau_4 s + 1}$$

Power injected into network

$$C = \frac{AB}{1 + AB}$$ Closed Loop DC gain

$$\tau_3 = \frac{\tau_1(1+\lambda)}{2(1+\gamma)}\left(1 + \sqrt{1 - \frac{4\lambda(1+\gamma)}{(1+\lambda)^2}}\right)$$

$$\tau_4 = \frac{\tau_1(1+\lambda)}{2(1+\gamma)}\left(1 - \sqrt{1 - \frac{4\lambda(1+\gamma)}{(1+\lambda)^2}}\right)$$

$$\lambda = \frac{\tau_2}{\tau_1} \qquad \gamma = AB$$

Linear approximation of the square root is used:

$$\sqrt{1+x} \approx 1 + \frac{x}{2}$$