Module 4a

Grid-Forming Inverters - Overview

What are they expected to do and what are the key differences to a grid-following inverter?

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Electrical Generator Expectations

- Controllable terminal voltage
- Controllable frequency

G. Denis, T. Prevost, M.-S. Debry, F. Xavier, X. Guillaud, and A. Menze, “The Migrate project: the challenges of operating a transmission grid with only inverter-based generation. A grid-forming control improvement with transient current-limiting control,” *IET Renewable Power Generation*, vol. 12, no. 5, pp. 523–529, 2018, doi: 10.1049/iet-rpg.2017.0369.

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- Stability maintained during outages/faults
- Some way to assess if $P_{in}=P_{out}$ (e.g. frequency)

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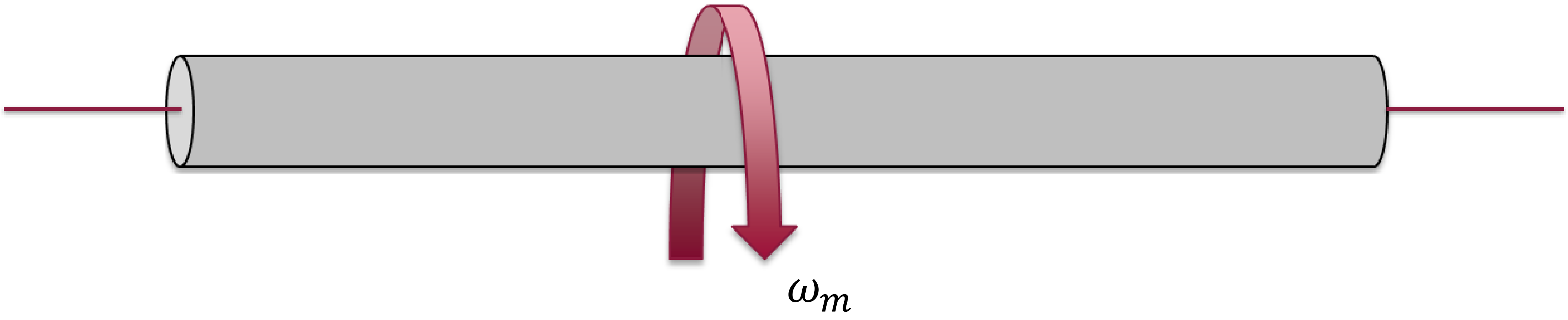
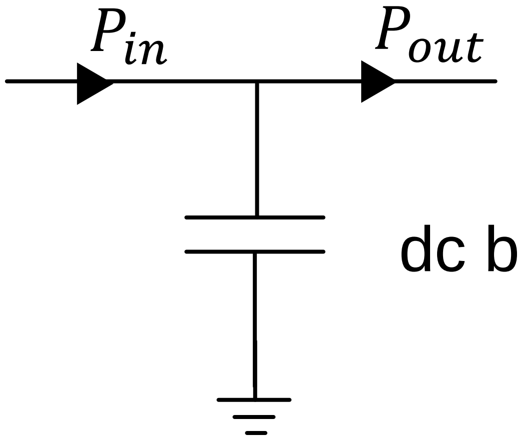
Reminder: Stability is Aided by System Inertia



$$E_{in} = \frac{1}{2} J \omega_m^2 + E_{out}$$

Energy differences cause shaft to speed up or slow down, degree depends on J

“Inertia” in an Inverter



dc bus capacitor

$$E_{in} = \frac{1}{2}CV^2 + E_{out}$$

<< $\frac{1}{2}J\omega_m^2$ in mechanical system

Energy differences cause capacitor voltage to change,
degree depends on C

However: Stability $\neq$ Inertia

- Inertia is an appendage of the SM grid scheme. You don’t *need* a spinning mass for the system to function
- It gives us **breathing room**

However: Stability $\neq$ Inertia

- Inertia is an appendage of the SM grid scheme. You don't *need* a spinning mass for the system to function
- It gives us **breathing room**
- IBRs don't have as much "energy reserve" but have much lower time constants

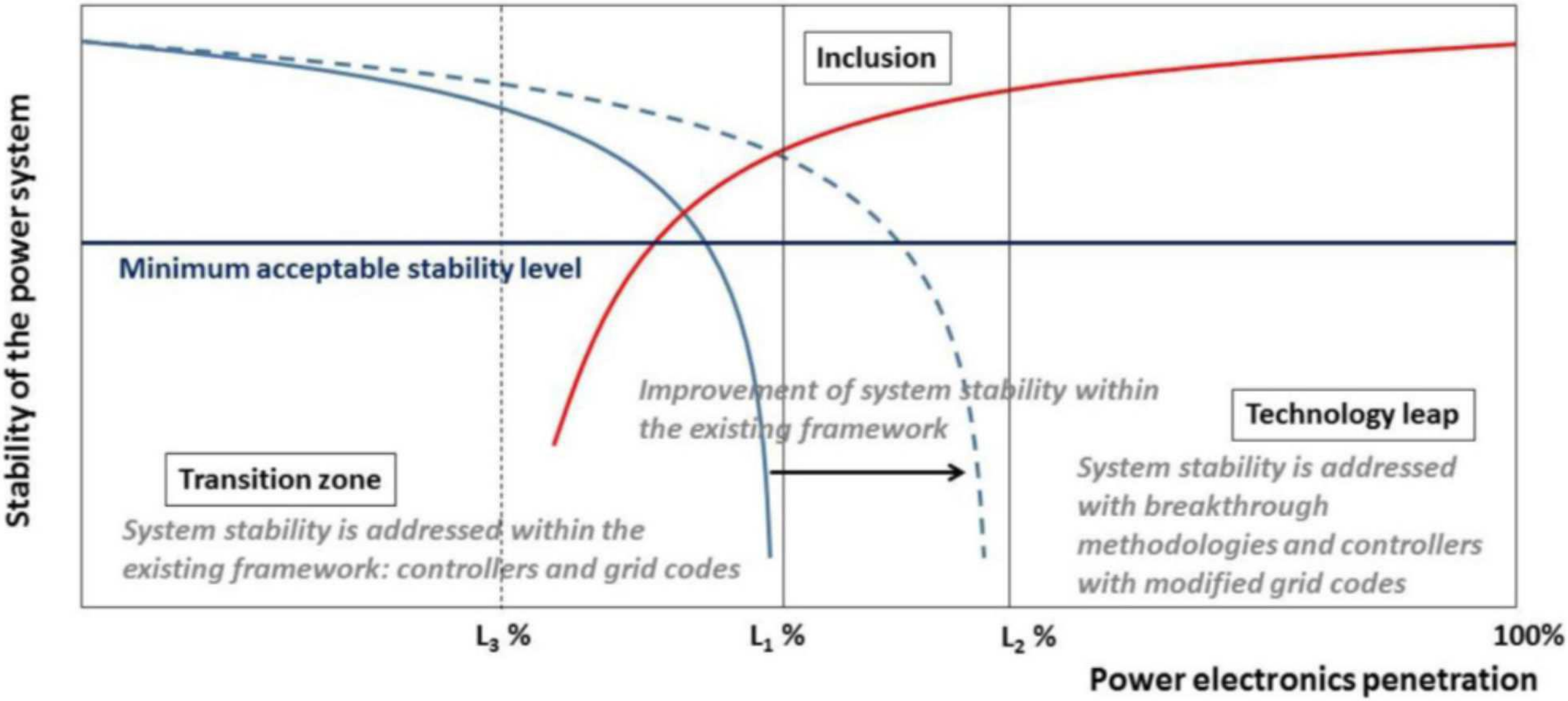
$$P = \frac{E}{t}$$

Higher in a machine

Lower in an IBR

- In principle, stability could be maintained with zero inertia. **All about getting $P_{in} = P_{out}$**

Transitioning to “100%” IBRs



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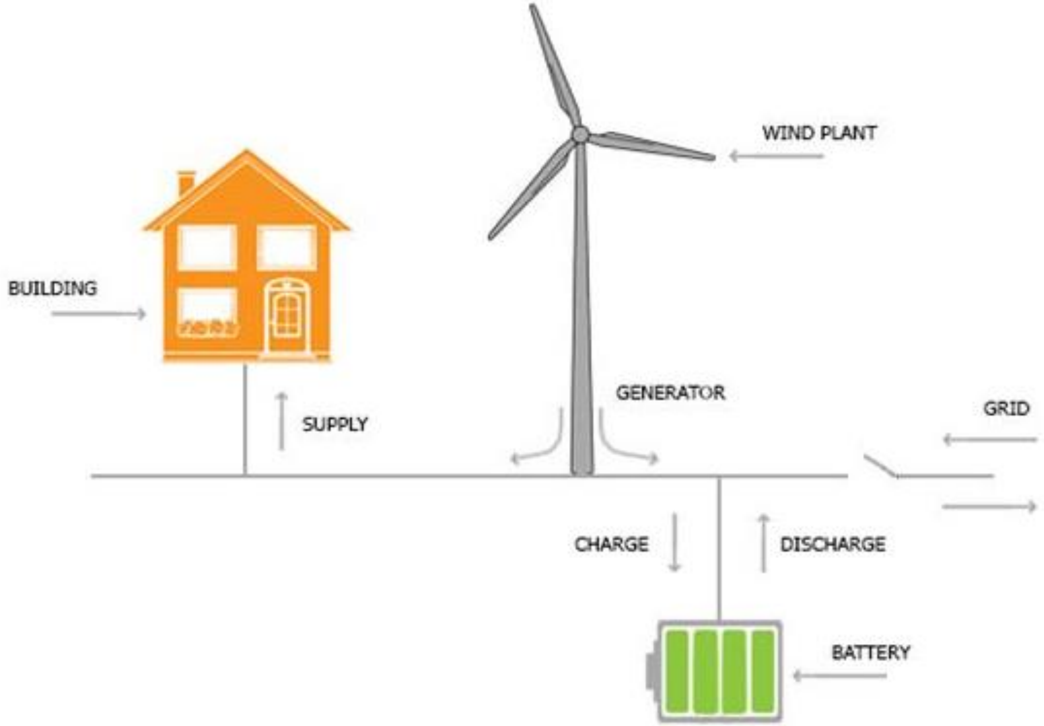
Useful Context: Microgrids

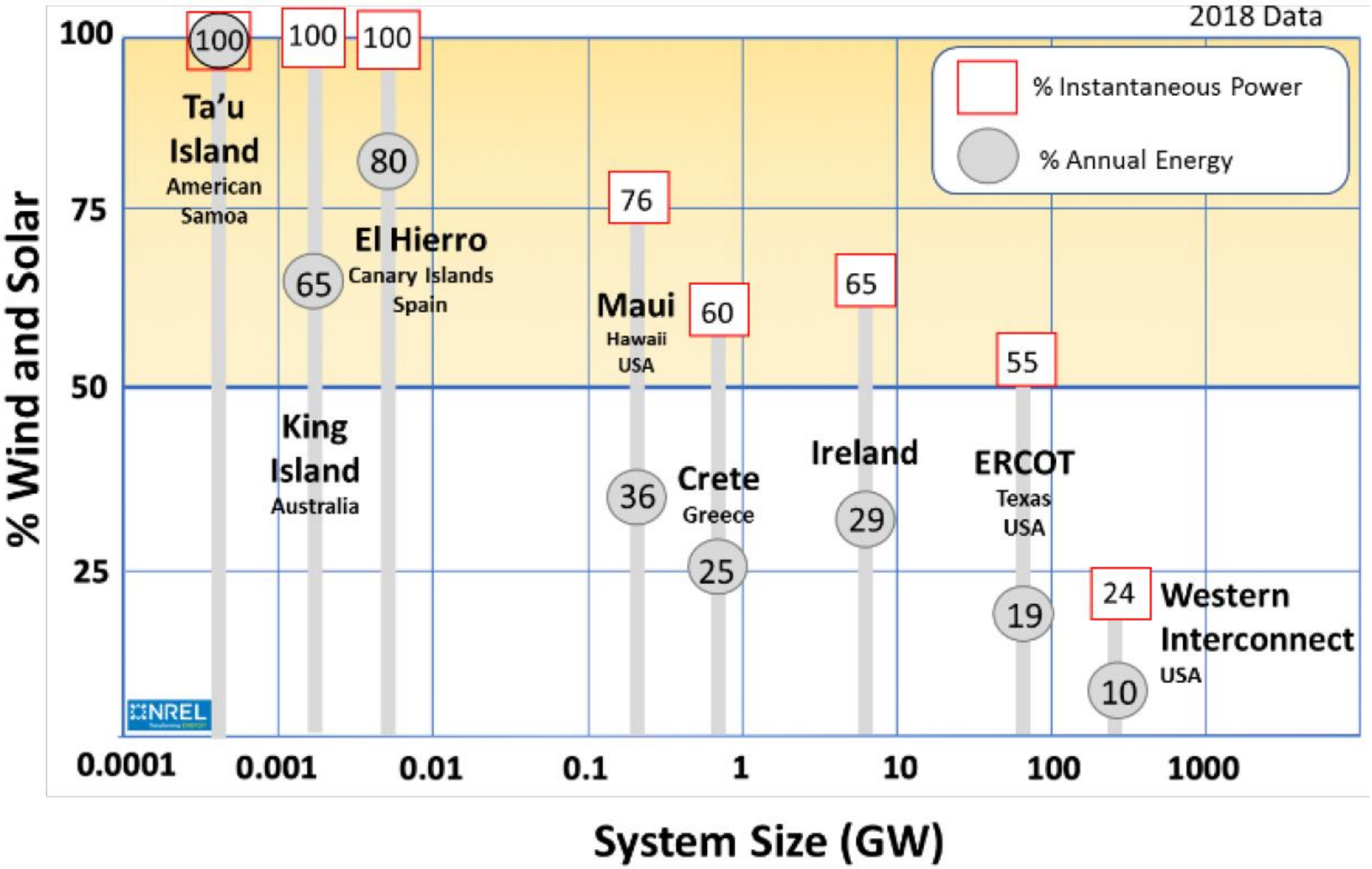


- A “small” grid (well-defined boundaries, small footprint)
- Includes distributed energy resources
- Ability to operate “islanded’ from the grid

- One or more inverters *must* be capable of regulating voltage and/or frequency!
- Grid-forming inverters originated from this, which is why research dates back decades

https://commons.wikimedia.org/wiki/File:Microgrid_with_RES_BESS_GRIDconnected.png

100% IBR Microgrids Exist



Y. Lin *et al.*, “Research Roadmap on Grid-Forming Inverters,” p. 60.

Module 4b

Grid-Forming Inverters – Control Strategies

How do we create a grid-forming inverter?

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Key Grid-Forming IBR Requirements

1. Functions autonomously and flexibly, regardless of rest of system (so, doesn’t depend on something else in the system to operate)

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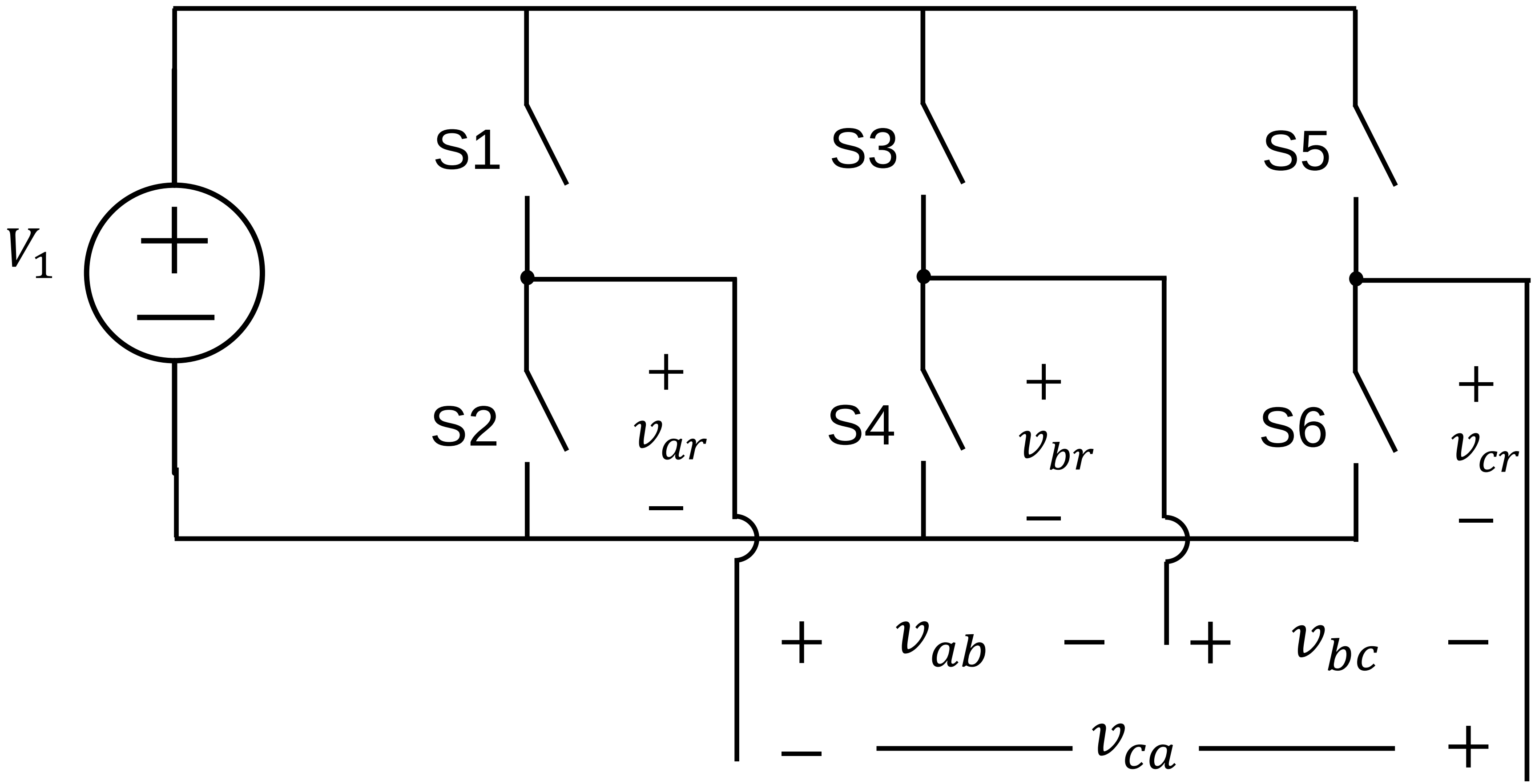
1. Functions autonomously and flexibly, regardless of rest of system (so, doesn’t depend on something else in the system to operate)
2. Ensure stability to contingencies
3. Provide controllable power up to their rating

These describe a controlled voltage source

Note: grid-following converters don’t do (1) or (2)!
They are controlled *current* sources

Three Major **Control** Strategies



We focus on innovations around the “standard” 3-leg inverter

Three Major Control Strategies

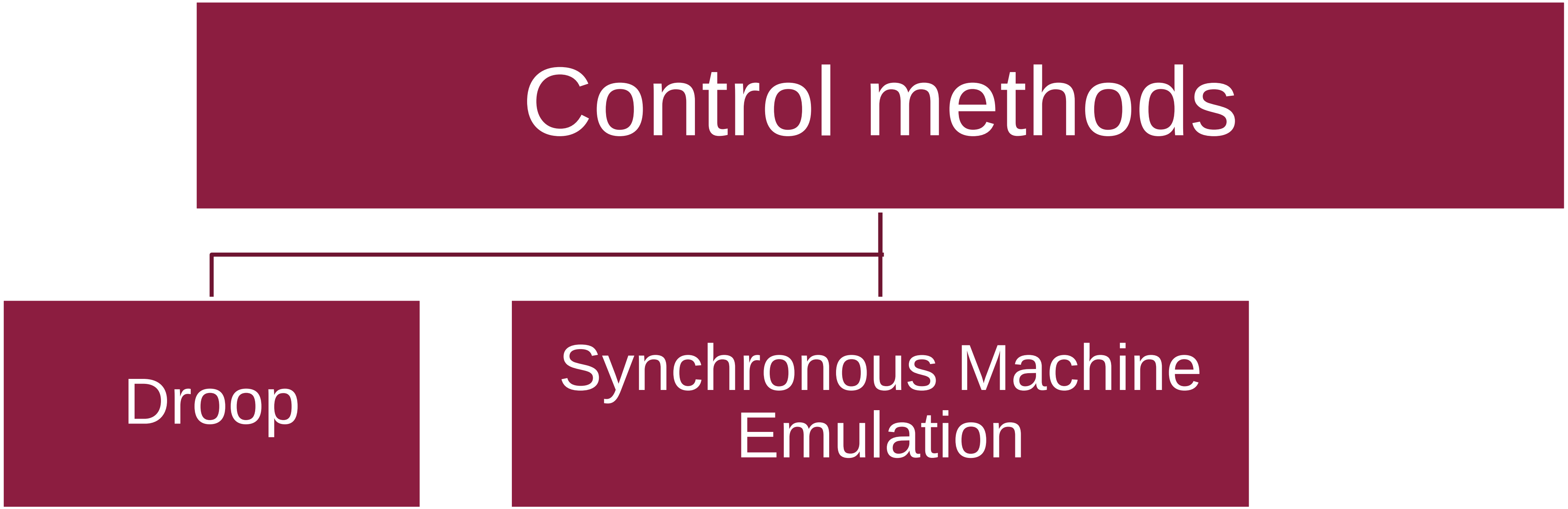
Control methods

Droop

- Simple implementation
- Analogous to mechanical control

D. B. Rathnayake et al., “Grid Forming Inverter Modeling, Control, and Applications,” IEEE Access, vol. 9, pp. 114781–114807, 2021, doi: 10.1109/ACCESS.2021.3104617.

Three Major Control Strategies


Control methods

Droop

Synchronous Machine Emulation

- Simple implementation
- Analogous to mechanical control

- More complicated implementation
- Direct inertia and damping properties

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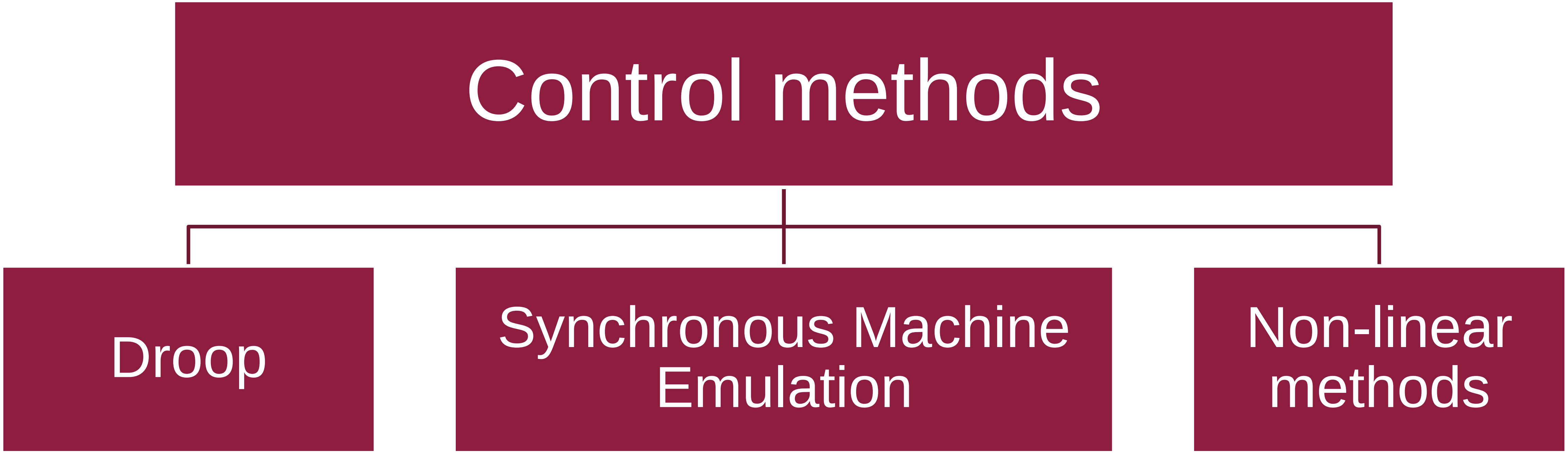


Control methods

Droop

Synchronous Machine Emulation

Non-linear methods

Droop

- Simple implementation
- Analogous to mechanical control

Synchronous Machine Emulation

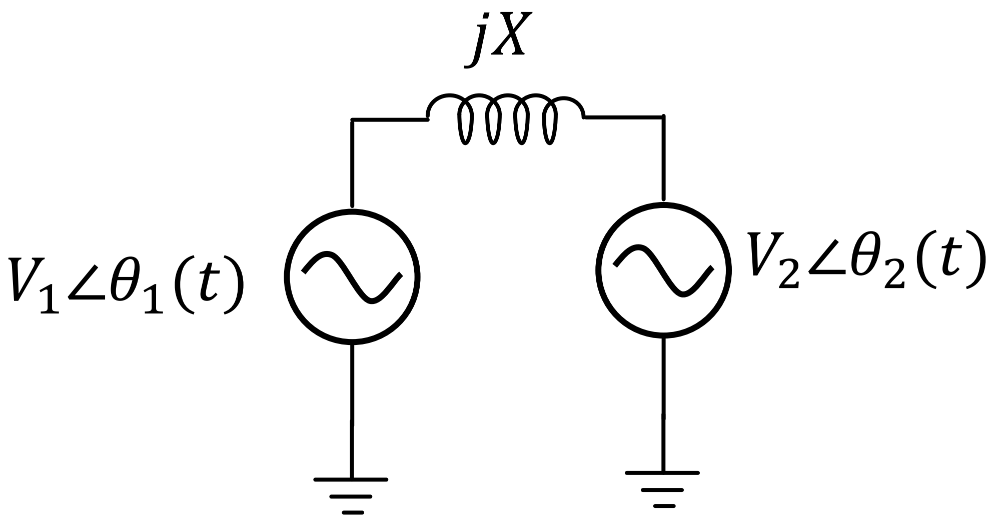
- More complicated implementation
- Direct inertia and damping properties

Non-linear methods

- Virtual oscillator control
- Time-domain control (no phasor quantities)

D. B. Rathnayake et al., “Grid Forming Inverter Modeling, Control, and Applications,” IEEE Access, vol. 9, pp. 114781–114807, 2021, doi: 10.1109/ACCESS.2021.3104617.

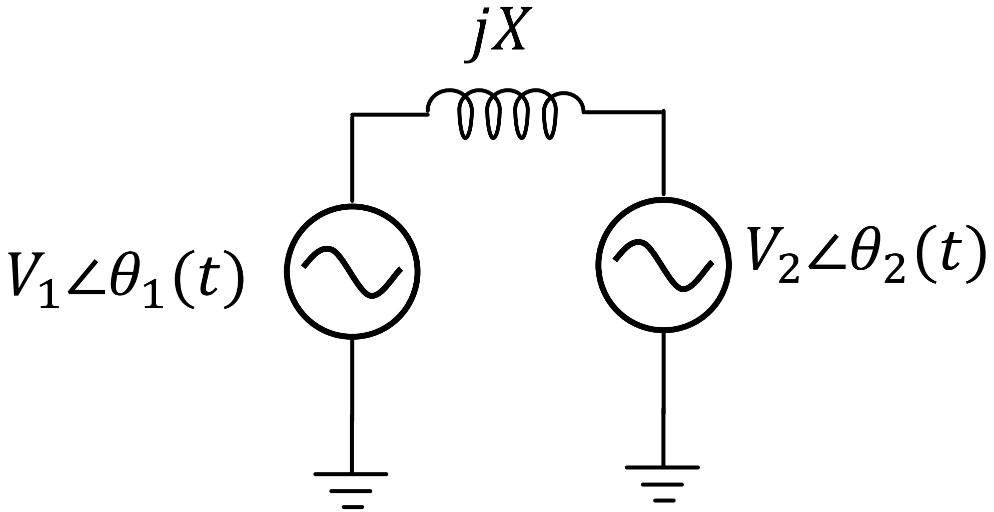
Power Transfer Between ac Voltage Sources



$$P_{1\to2}(t) = \frac{V_1V_2\sin\big(\theta_2(t) - \theta_1(t)\big)}{X}$$

Power transfer depends on angle difference

Power Transfer Between ac Voltage Sources



$$P_{1\rightarrow 2}(t) = \frac{V_1 V_2 \sin\big(\theta_2(t) - \theta_1(t)\big)}{X}$$

Power transfer depends on angle difference

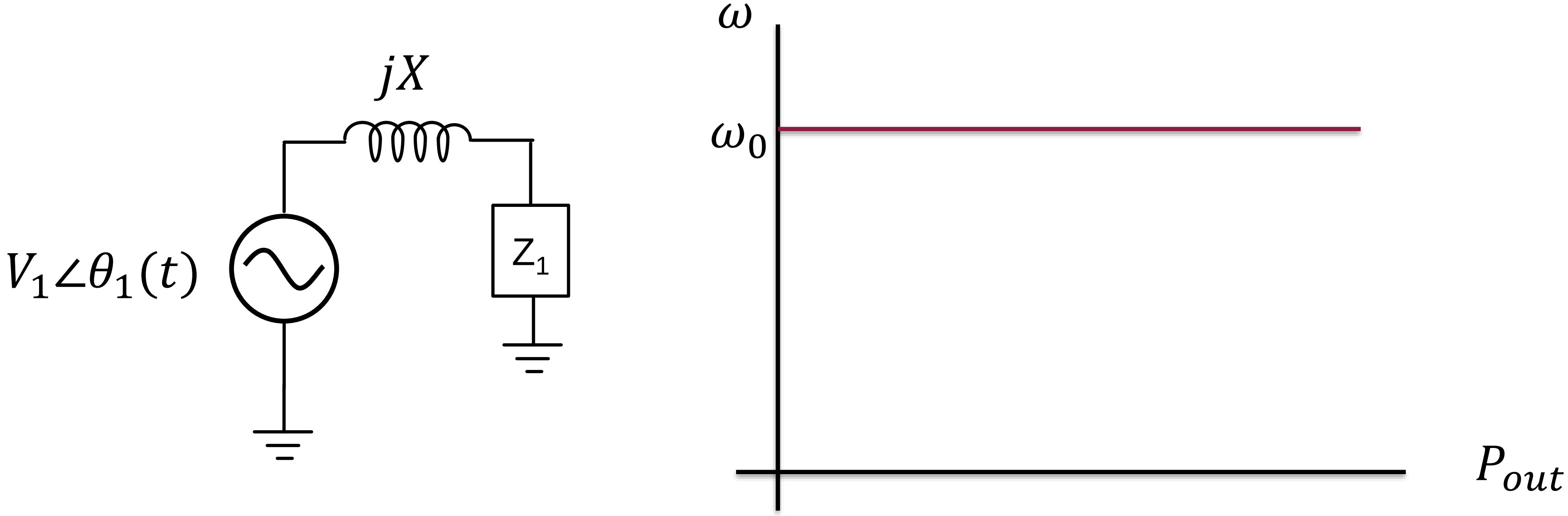
$$\theta_i(t) = \int \omega_i(t)\, dt$$

Angles depend on frequency reference

Therefore, power transfer and frequency command are coupled

Simple/Intuitive Control of Frequency

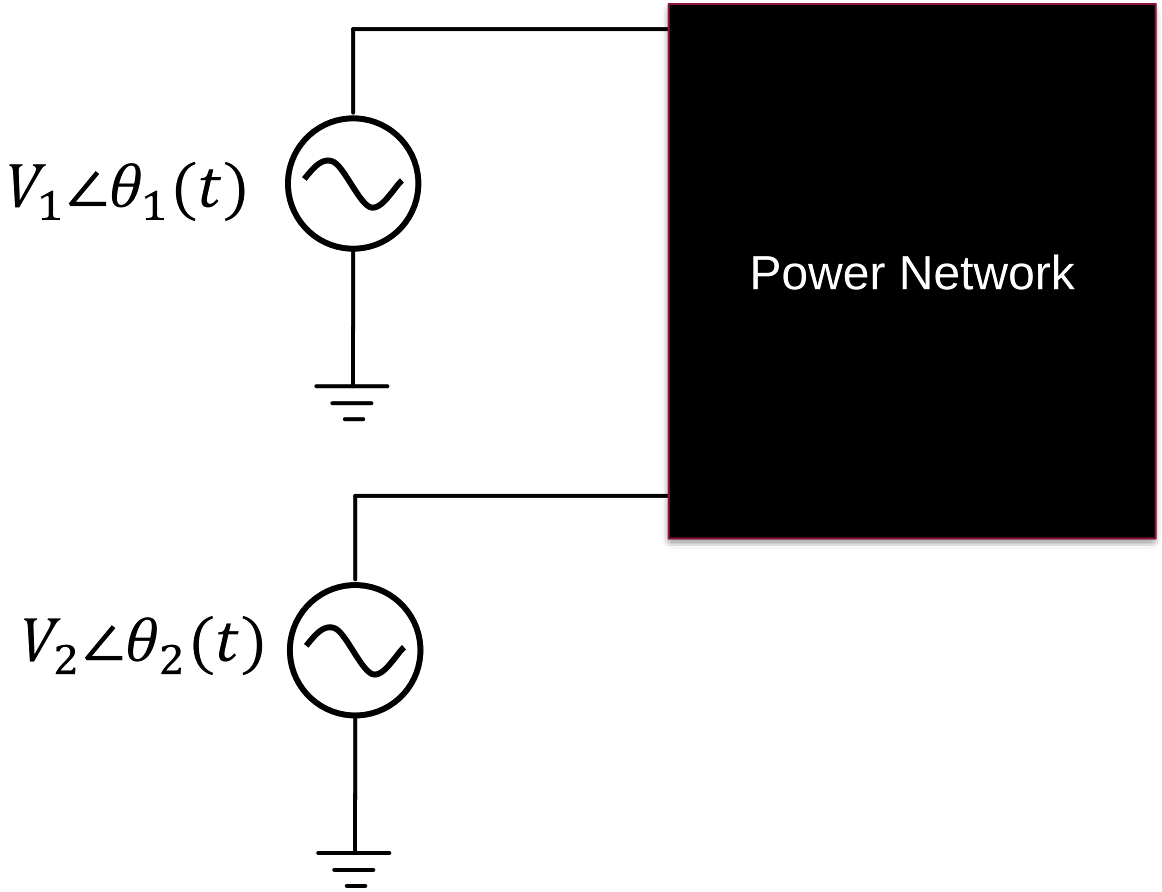
- Crucial that system frequency be within tight specification
- Simple option: Always regulate to ω_0



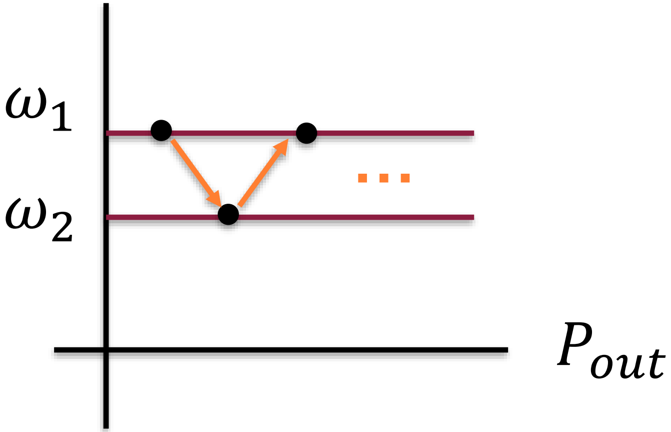
“Isochronous” Control

Sensible for a single generator system

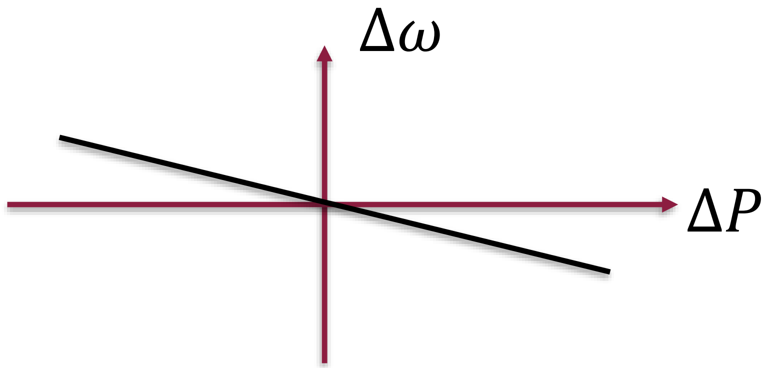
Problem: Parallel Generators



- Each generator frequency unlikely to be exactly equal, or to match with network frequency
- Generators will “fight” to take control of system frequency
- Inherently unstable



Solution: Droop Control



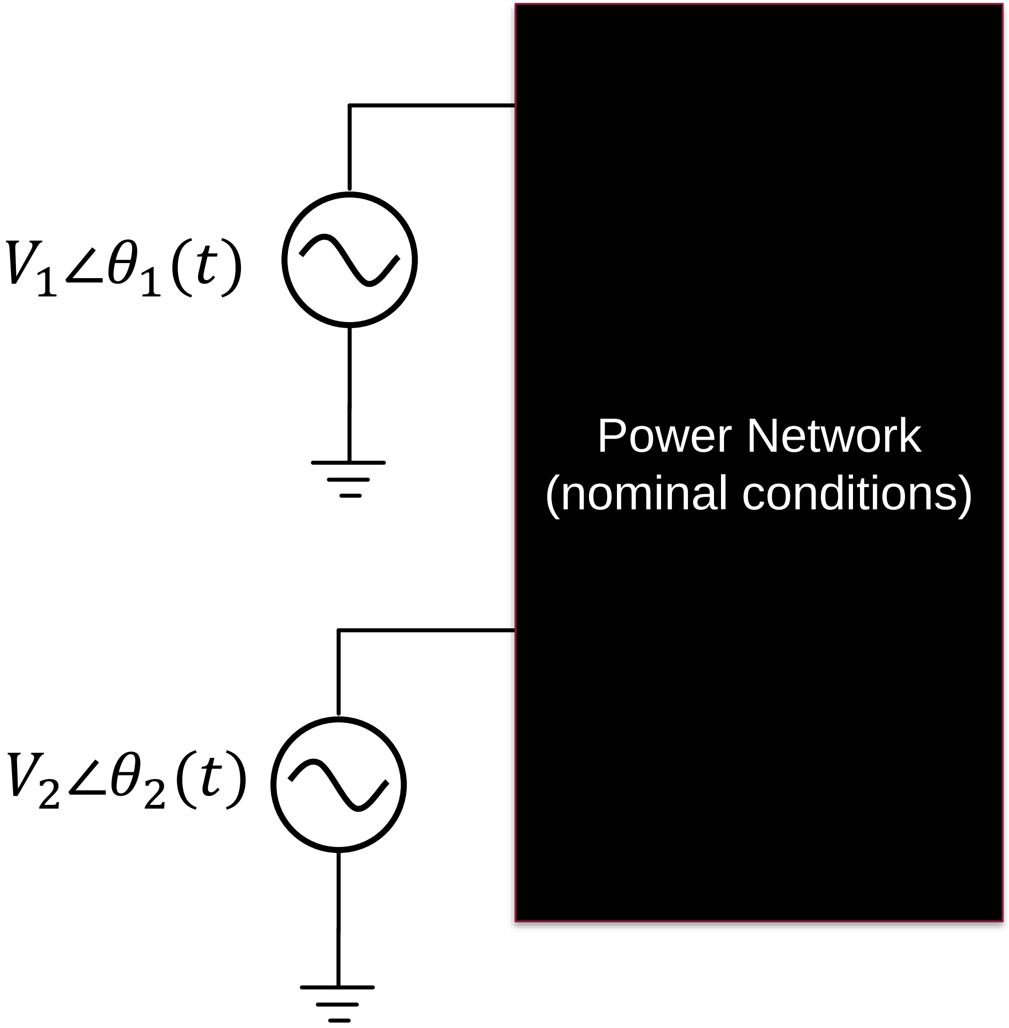
← Output power

- Allow generator frequency to deviate linearly with output power

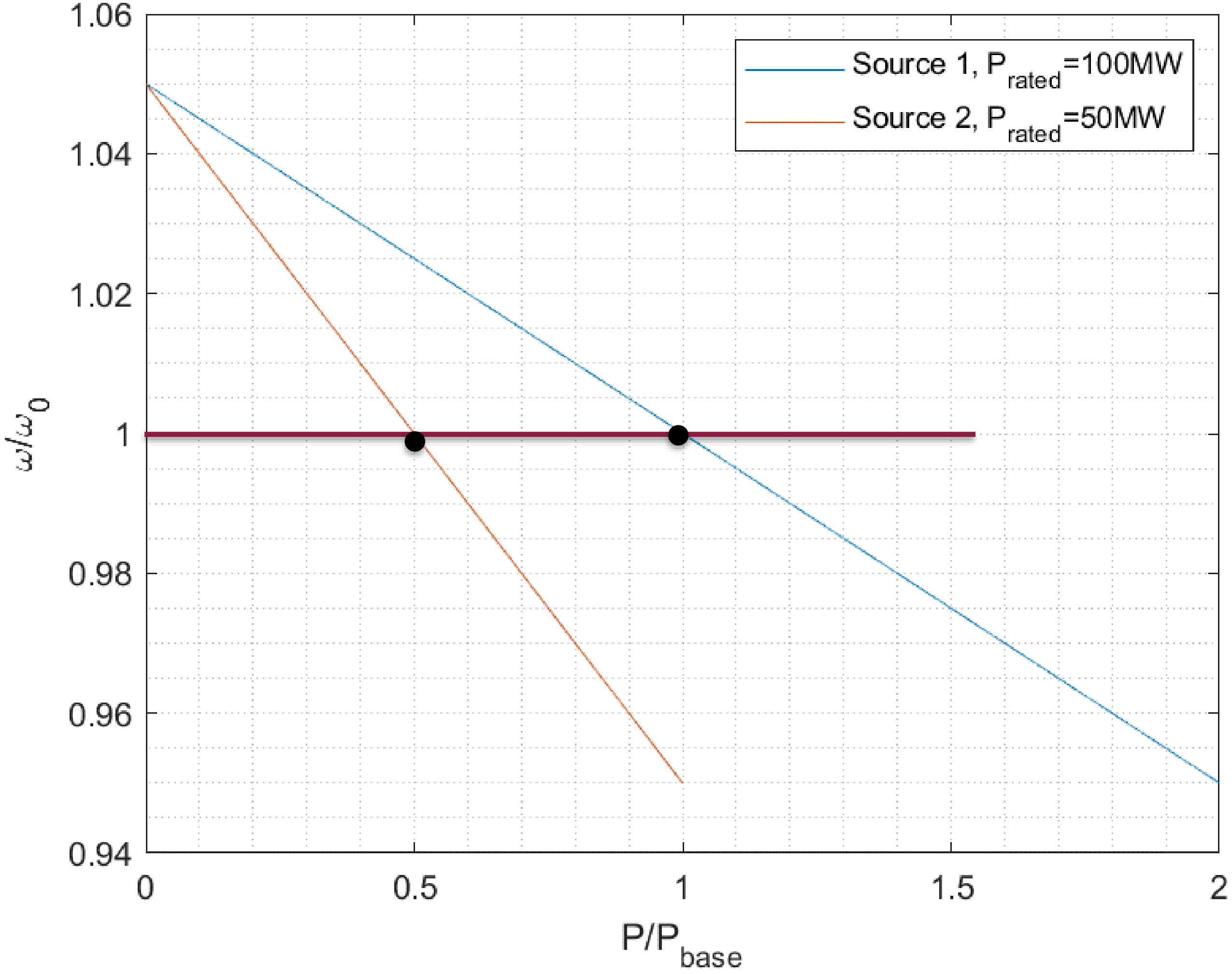
- An SM naturally has speed drop for a sudden increase in load demand (sudden output power increase), so this concept draws from that principle.

- Key: Set generator droop slopes such that $m_1 P_1 = m_2 P_2 = \cdots = m_i P_i$

Example: Droop Power-Sharing Example

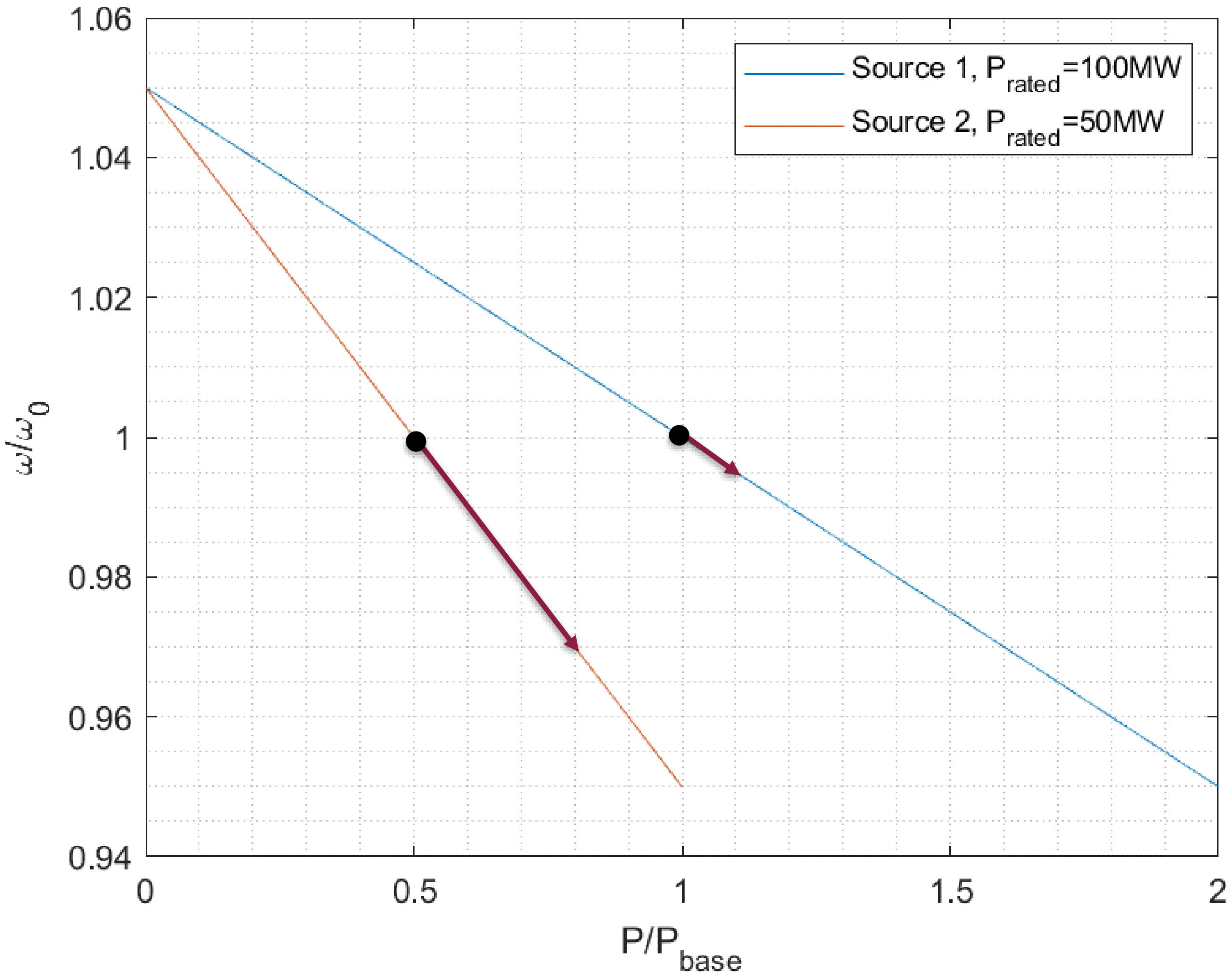


$m_2 = 2m_1$ since $P_1 = 2P_2$



Example Droop Power-Sharing Example

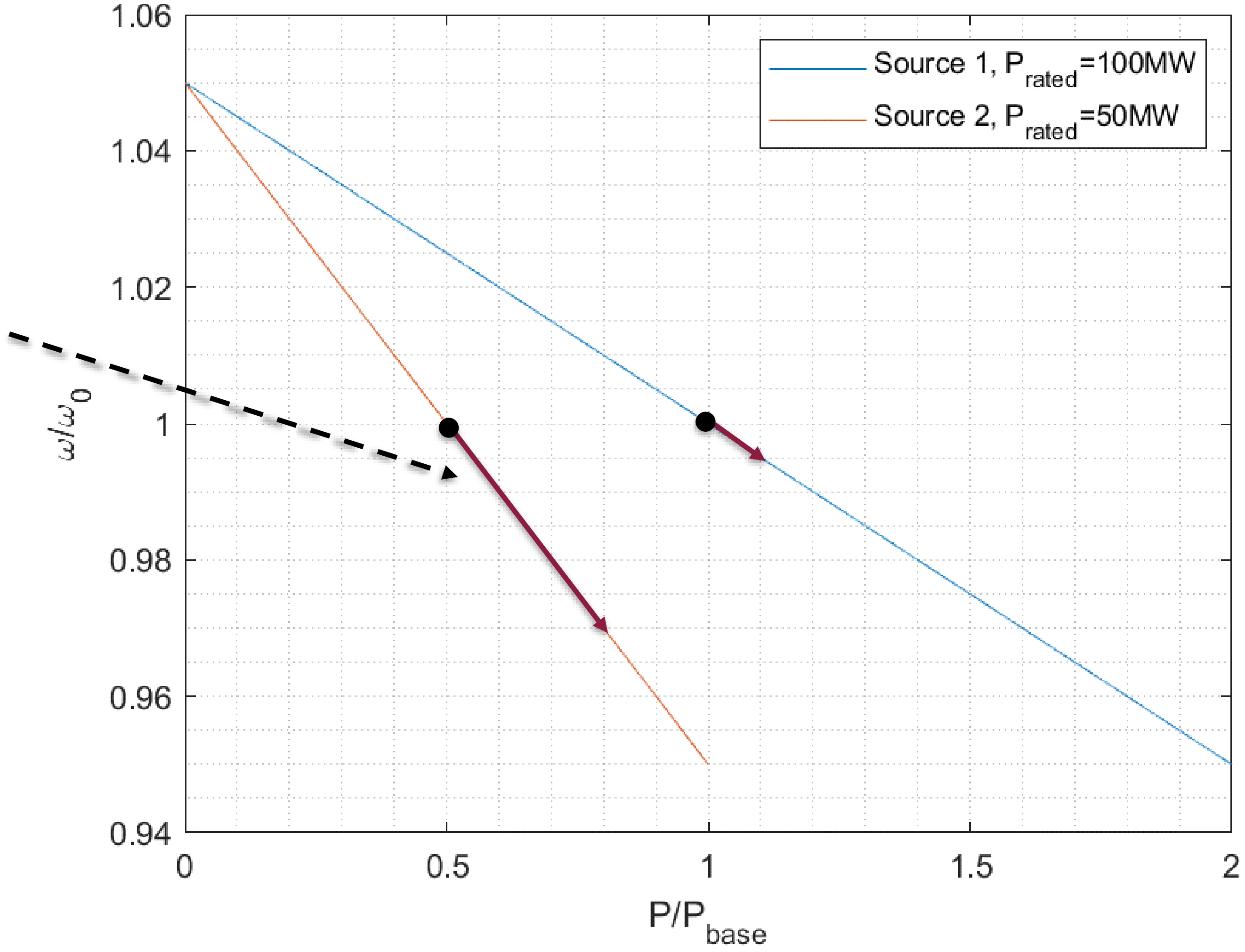
1. Power demand increases, both sources deliver more power



Example Droop Power-Sharing Example

1. Power demand increases, both sources deliver more power

2. Smaller source has higher droop, its frequency drops faster, increases lag to larger source



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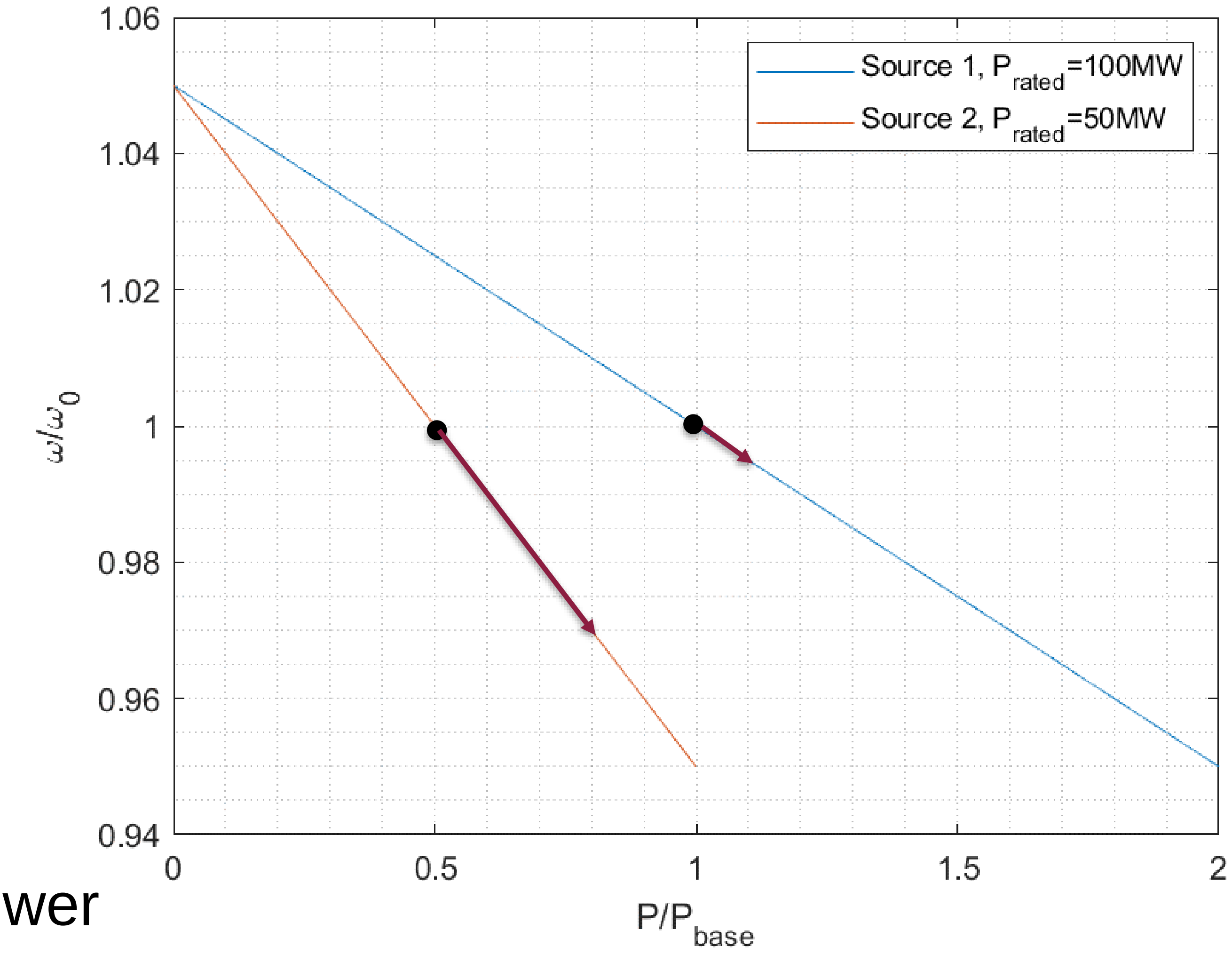
Power flows from leading to lagging sources ⇒ Source 1 delivers more power



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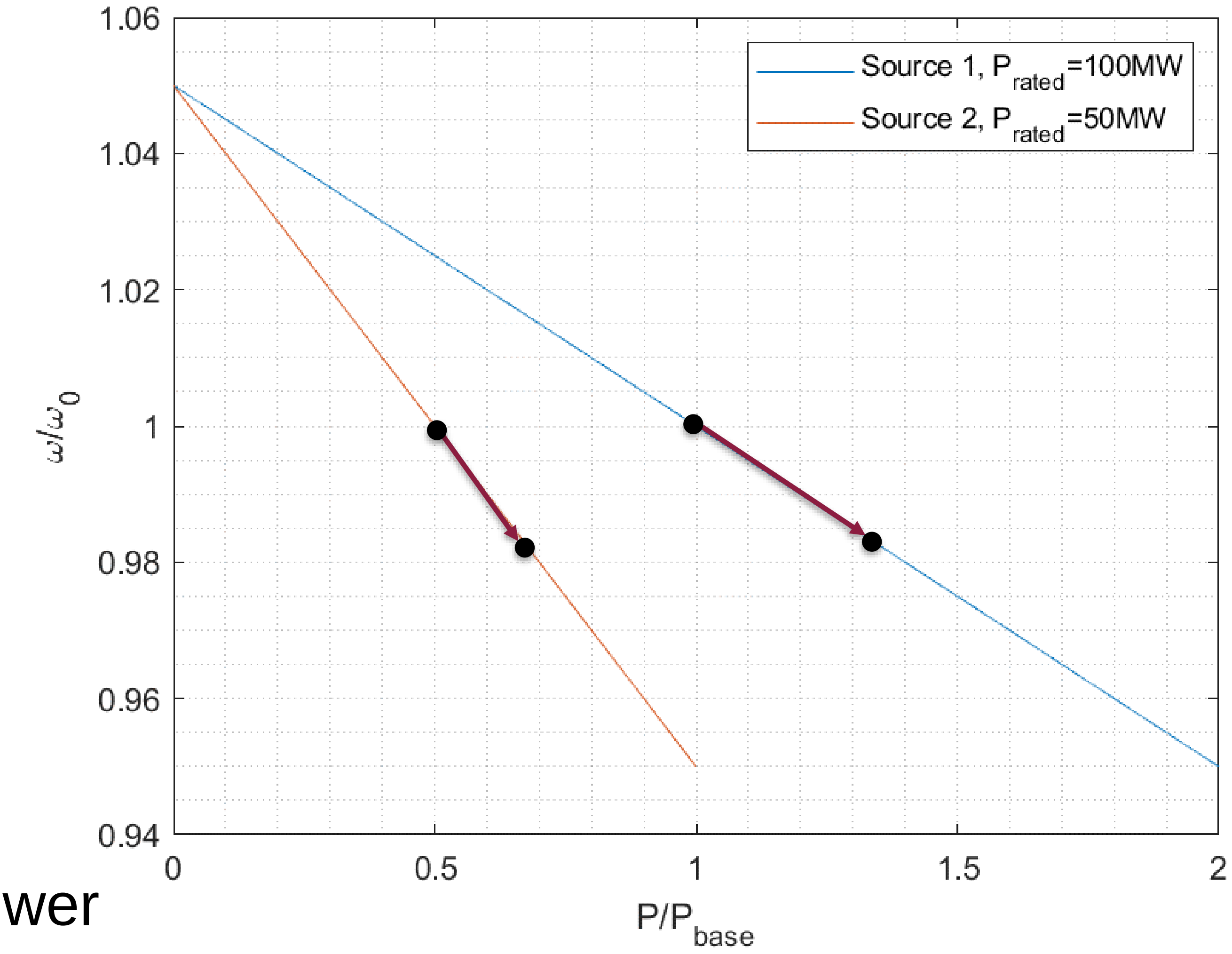

3. Inverters take up new load in correct proportion

Example Droop Power-Sharing Example

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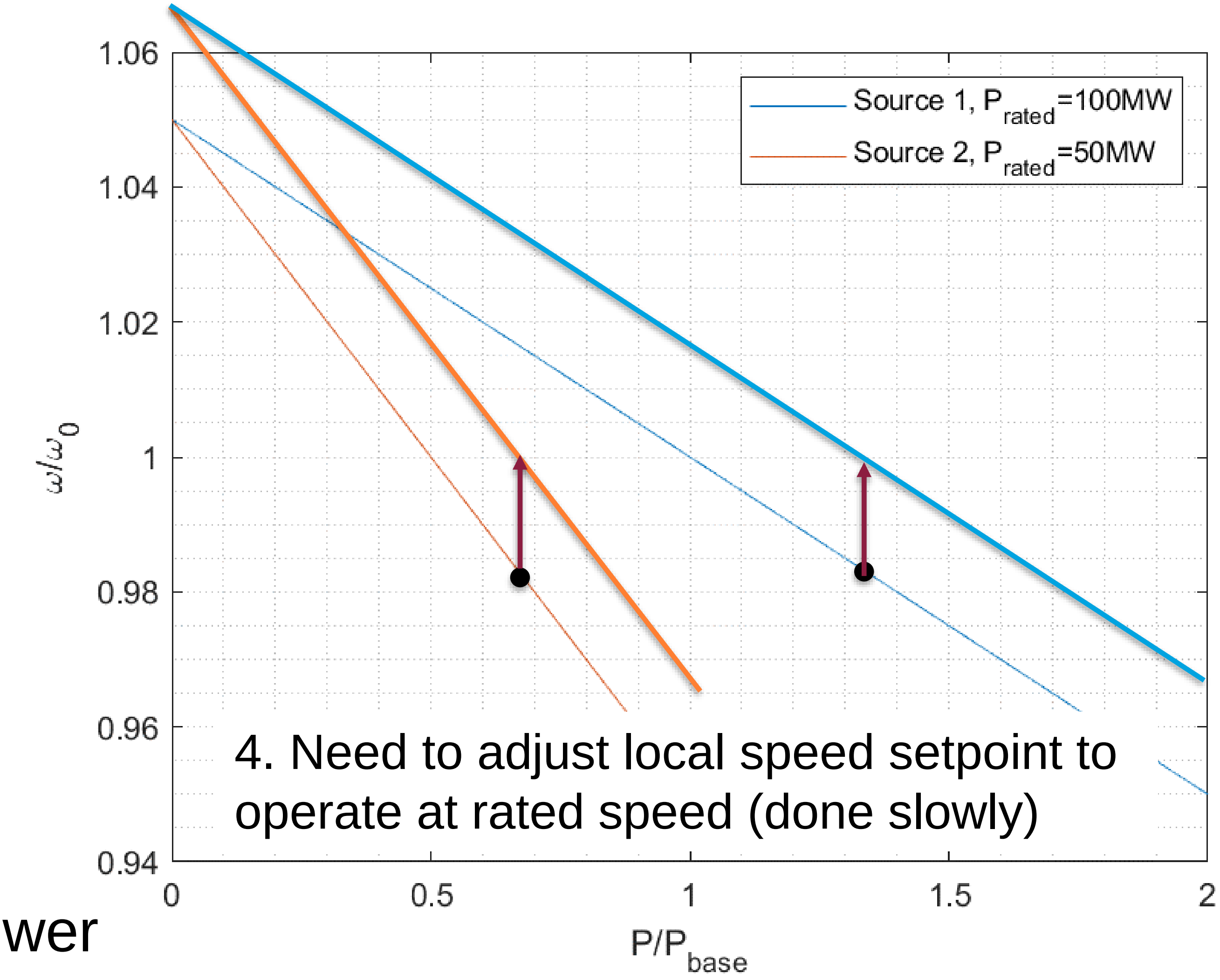
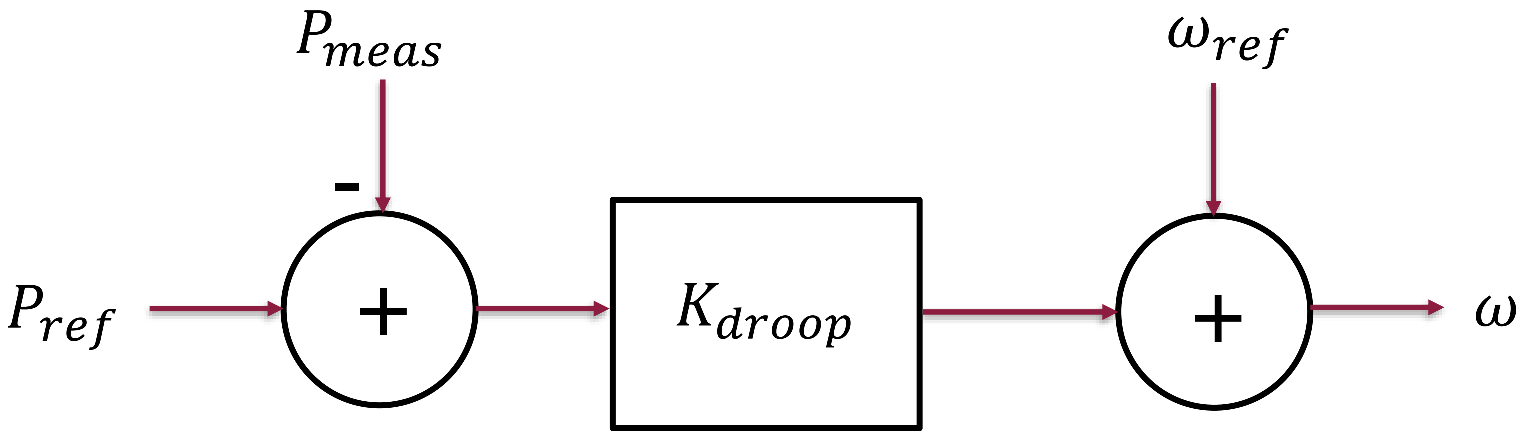
Power flows from leading to lagging sources ⇒ Source 1 delivers more power

3. Generators take up new load in correct proportion

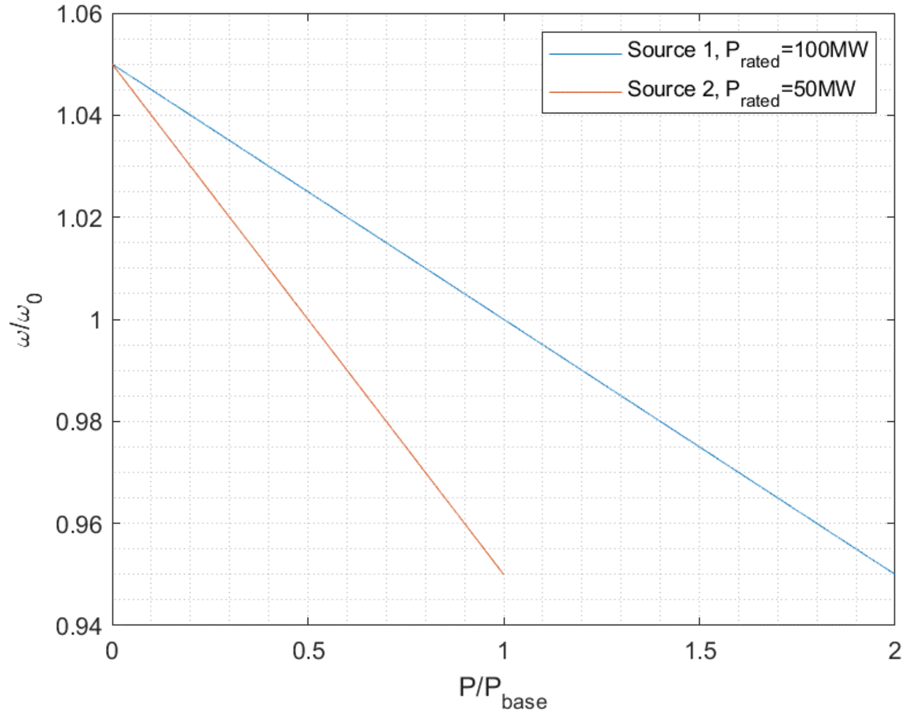


4. Need to adjust local speed setpoint to operate at rated speed (done slowly)

Control Implementation



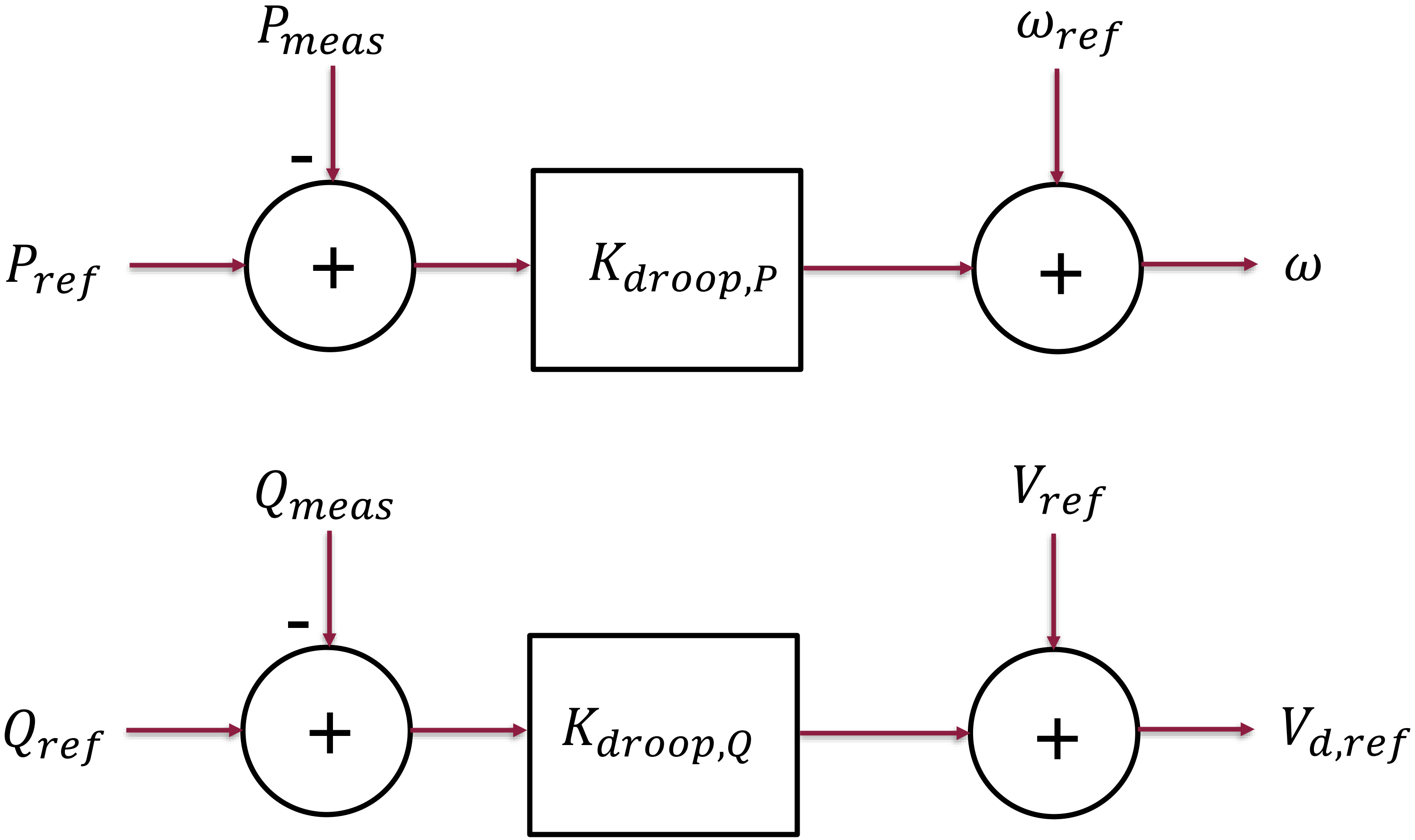
$$\omega = K_{droop}\left(P_{ref} - P_{meas}\right) + \omega_{ref}$$



Simple linear implementation
If P_{meas} goes up, reduce speed proportionally

D. B. Rathnayake et al., “Grid Forming Inverter Modeling, Control, and Applications,” IEEE Access, vol. 9, pp. 114781–114807, 2021, doi: 10.1109/ACCESS.2021.3104617.

Same Idea for Q Control



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Droop Control Summary

- Applies generally to generators, originally used in control of SMs and extended for inverters
- Autonomous load sharing with simple linear control implementation
- No “inertia” embedded in control, can have high ROCOF
- Requires energy storage for dispatchable power (more soon)

Module 4c

Grid-Forming Inverters – Synchronous Machine Emulation

Another popular linear control technique

Arizona State University

One Step Farther than Droop Control

- Droop control was derived to mimic control of the grid-connected synchronous generator
- Go one step further, mimic the synchronous generator

Black-box SM Behaviour

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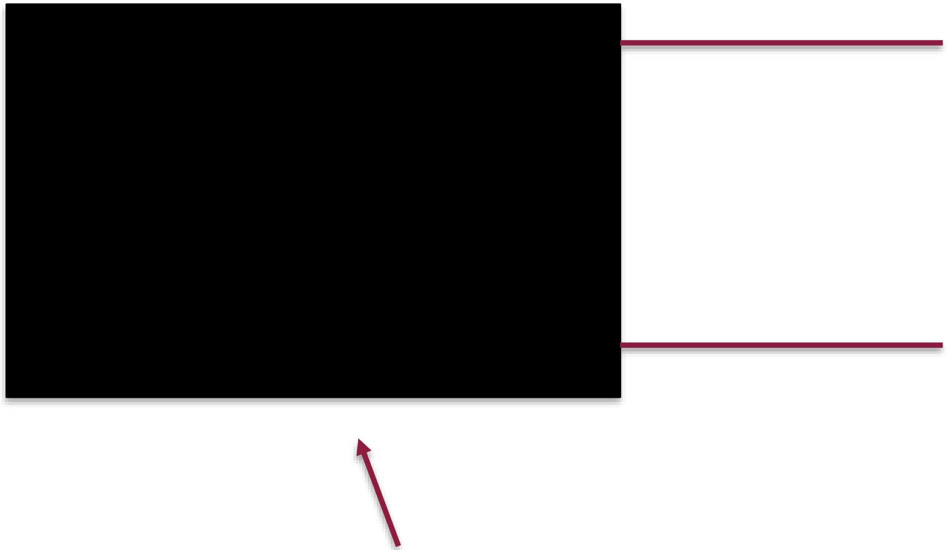
- Go one step further, mimic the synchronous generator



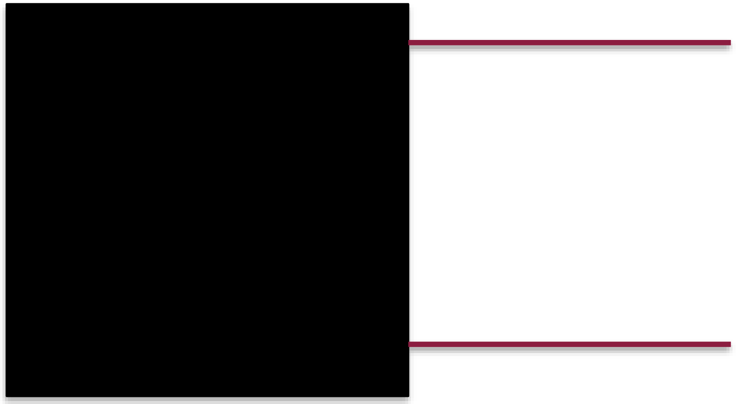
e.g. Swing equation

$$\boxed{M\ddot{\delta} + D\dot{\delta} = p_m - p_e}$$

$$\boxed{J\omega_m\ddot{\delta} + 2k\omega_m\dot{\delta} = P_m - P_e}$$

Doesn’t **have to** be a synchronous machine,
just needs to **behave** like one

Control Inverter to Behave like SM



1. Measure *v*, *i*
2. Solve inverter dynamics based on programmed machine quantities
3. Inverter outputs these quantities

$$\boxed{M\ddot{\delta} + D\dot{\delta} = p_m - p_e}$$

- Key difference: since M, D are “virtual” they can be programmed on-the-fly, yielding control flexibility

Many Levels of Granularity

Swing Equation
(“First swing” inertia)

Increasing complexity

<u>“Synchronverter”</u>

Precise electromechanical model (stator, damper, excitation windings; virtual torque and excitation voltages)

Emulating Swing Equation

Recalling Module 1, we can rewrite the swing equation as:

$$J\omega_m \frac{d}{dt}(\omega - \omega_m) + 2k\omega_m(\omega - \omega_m) = P_m - P_e$$

- ω is rotational speed of the rotor
- ω_m is nominal rotational speed (e.g. grid frequency, recall swing equation considers changes about this frequency)
- J is moment of inertia
- k is damping coefficient

M. Li *et al.*, “A novel virtual synchronous generator control strategy based on improved swing equation emulating and power decoupling method,” in *2016 IEEE Energy Conversion Congress and Exposition (ECCE)*, Sep. 2016, pp. 1–7. doi: 10.1109/ECCE.2016.7854751.

Swing Equation Control Law

$$J\omega_m \frac{d}{dt}\left(\omega - \omega_{ref}\right) + 2k\omega_m\left(\omega - \omega_{ref}\right) = P_{ref} - P_e$$

Call mech. quantities “reference”

$$\underbrace{J\omega_m}_{\text{Call this } M_1} \frac{d}{dt}\Delta\omega + \underbrace{2k\omega_m}_{\text{Call this } D_1}\Delta\omega = \Delta P$$

(Not per unit)

Swing Equation Control Law

$$\underbrace{J\omega_m}_{\text{Call this } M_1}\frac{d}{dt}\Delta\omega + \underbrace{2k\omega_m}_{\text{Call this } D_1}\Delta\omega = \Delta P$$

(Not per unit)

$$M_1\frac{d}{dt}\Delta\omega + D_1\Delta\omega = \Delta P$$

Re-write

Swing Equation Control Law

$$\underline{J\omega_m}\frac{d}{dt}\Delta\omega + \underline{2k\omega_m}\Delta\omega = \Delta P$$

Call this M_1

Call this D_1

(Not per unit)

$$M_1\frac{d}{dt}\Delta\omega + D_1\Delta\omega = \Delta P$$

Re-write

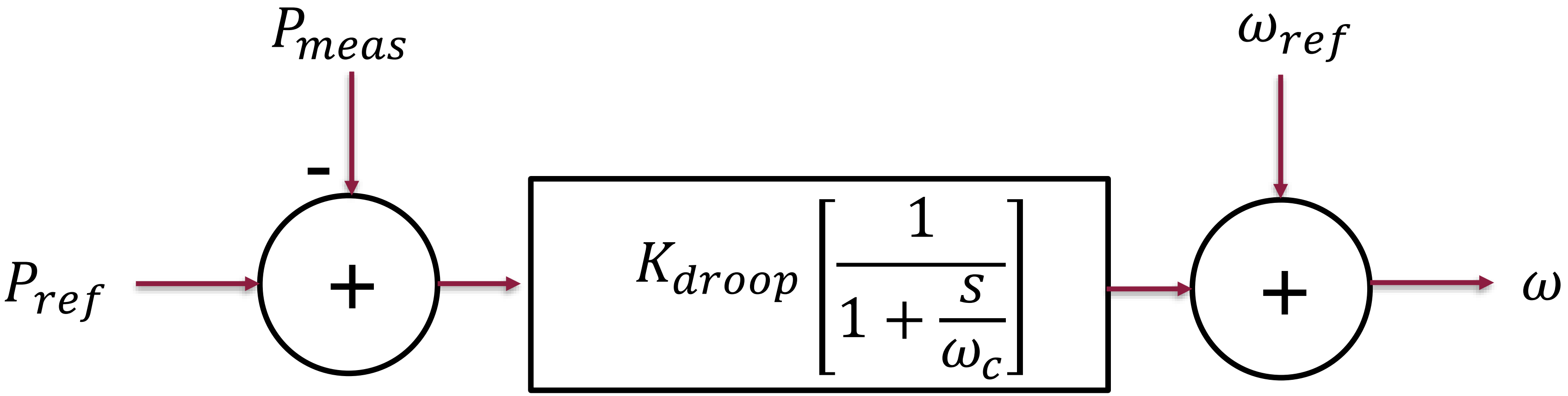
$$\Delta\omega(M_1 s + D_1) = \Delta P$$

Laplace

$$\Delta\omega = \frac{1}{(D_1)}\frac{\Delta P}{\left(1 + \frac{M_1}{D_1}s\right)}$$

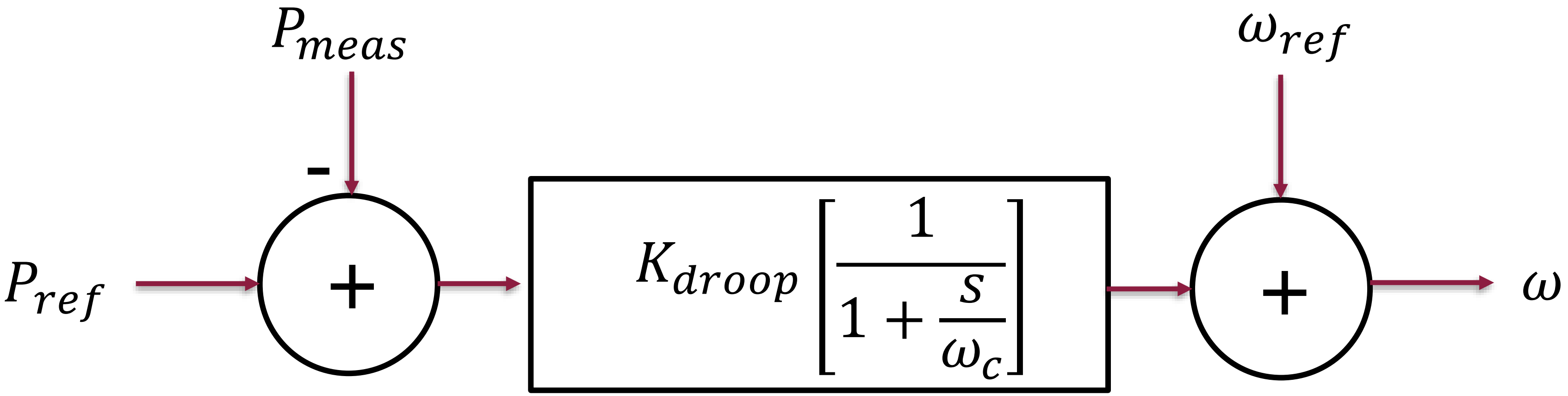
Looks like a droop law
(e.g. set $M_1 = 0$, $1/D_1 = K_{droop}$)
Though D_1 typically positive

Droop Control with Low-Pass Filter



- Typically needed to filter out harmonics and measurement noise

Droop Control with Low-Pass Filter



- Typically needed to filter out harmonics and measurement noise

$$\Delta\omega = K_{droop}\frac{\Delta P}{\left(1+\frac{s}{\omega_c}\right)}$$

vs

$$\Delta\omega = \frac{1}{(D_1)}\frac{\Delta P}{\left(1+\frac{s}{D_1/M_1}\right)}$$

These are mathematically equivalent, droop is a “special case” of SM emulation

Summary of SM Emulation

- Control inverter to behave like synchronous machine, direct programming of damping and inertia
- Damping coefficient of the virtual machine mimics droop coefficient, get autonomous sharing
- Implementations vary in accuracy and precision
- Again, requires energy storage for dispatchable power

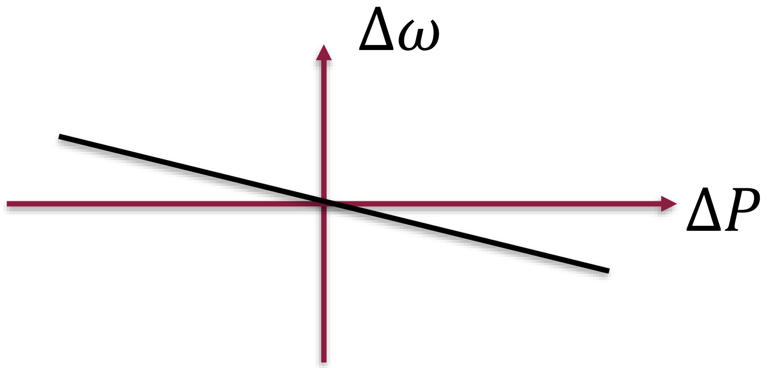
Module 4d

Grid-Forming Inverters – Virtual Oscillator Control

A non-linear control method

Arizona State University

Droop and SM Emulation Involve Phasor Quantities



- Perform multiplication of current and voltage
- Employ low cut-off low-pass filters to extract averages
  - Trade-off between harmonic immunity and bandwidth

These are “speed bumps” to a fast, high-bandwidth, controller

B. Johnson, M. Rodriguez, M. Sinha, and S. Dhople, “Comparison of virtual oscillator and droop control,” in *2017 IEEE 18th Workshop on Control and Modeling for Power Electronics (COMPEL)*, Stanford, CA, USA, Jul. 2017, pp. 1–6. doi: 10.1109/COMPEL.2017.8013298.

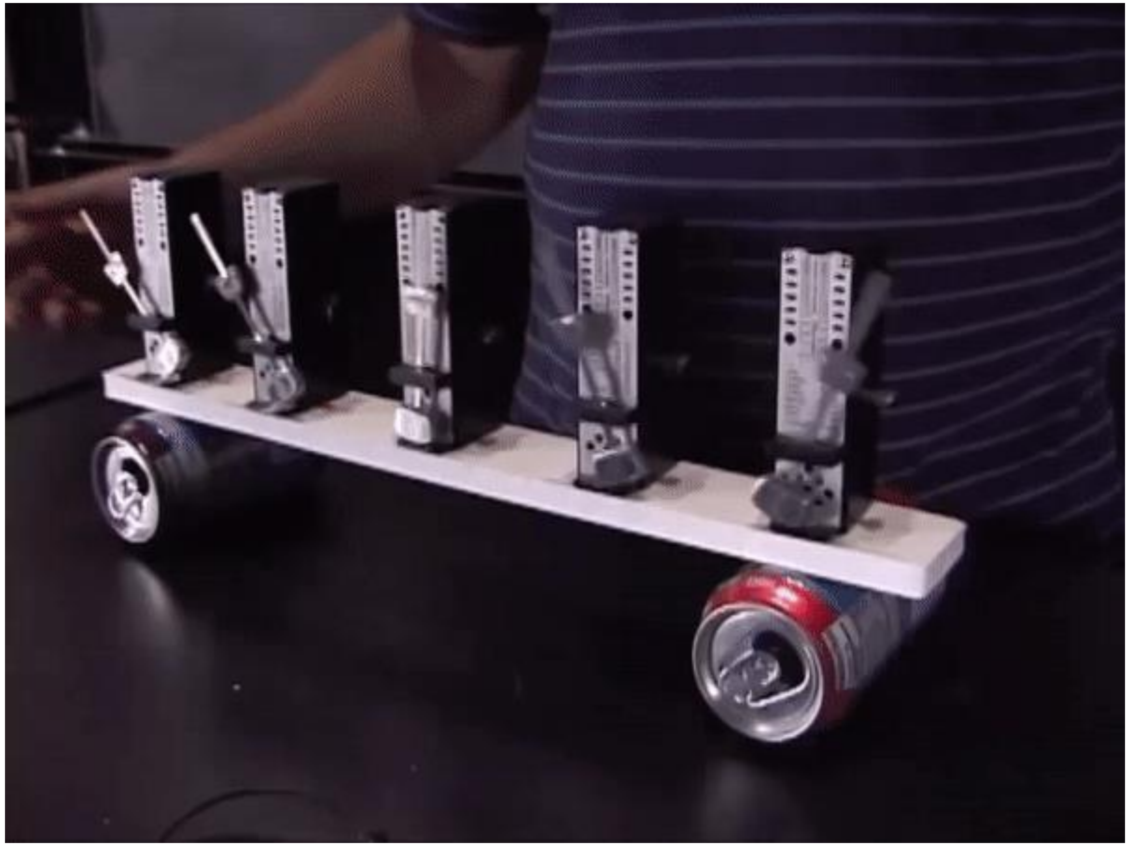
A Non-linear Control Principle

- Recall, we can make the inverter “look like anything” behind its terminals by employing appropriate control

- SM Emulation – make it look like a synchronous machine

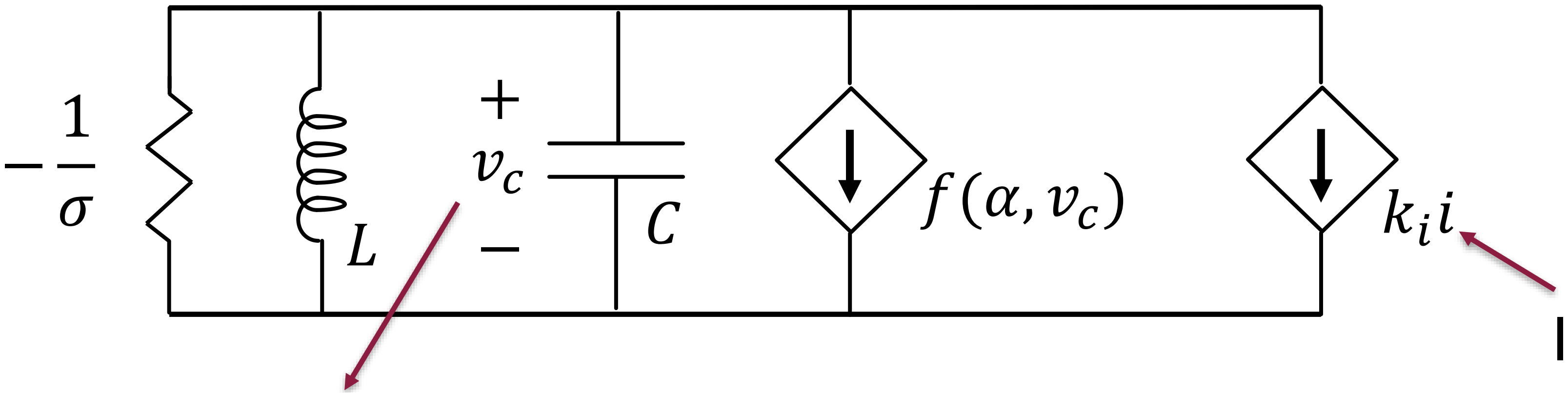
- Virtual Oscillator Control (VOC) – make it look like an oscillator

Weakly Coupled Oscillators Naturally Synchronize



Harvard Natural Sciences Lecture Demonstrations. “Synchronization of Metronomes,” *YouTube*, June 8, 2010 [Video file]. Available: https://www.youtube.com/watch?v=Aaxw4zbULMs. [Accessed: Jan. 25, 2022]

Digital VOC Implementation



ϵv_c output inverter command

Inverter
current
input

- Natural (LC) frequency = grid frequency
- Model parameters $\{\sigma, f(\alpha, v_c), k_i, \epsilon\}$ tuned for desired performance (droop, settling time, peak voltages/currents)
- Only “one-cycle” moving average needed

B. Johnson, M. Rodriguez, M. Sinha, and S. Dhople, “Comparison of virtual oscillator and droop control,” in *2017 IEEE 18th Workshop on Control and Modeling for Power Electronics (COMPEL)*, Stanford, CA, USA, Jul. 2017, pp. 1–6. doi: 10.1109/COMPEL.2017.8013298.

Virtual Oscillator Control Summary

- Non-linear control techniques allow for direct mapping of time-domain based algorithms (e.g. virtual oscillator control, “greedy” control)

- VOC mimics the inherent spontaneous synchronization of weakly coupled oscillators

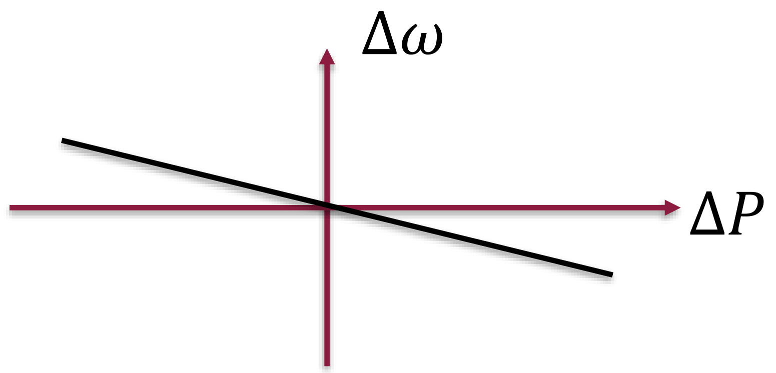
- Time-domain based control can be much faster than phasor-based control; trade-off is complexity and inapplicability of conventional linear toolbox

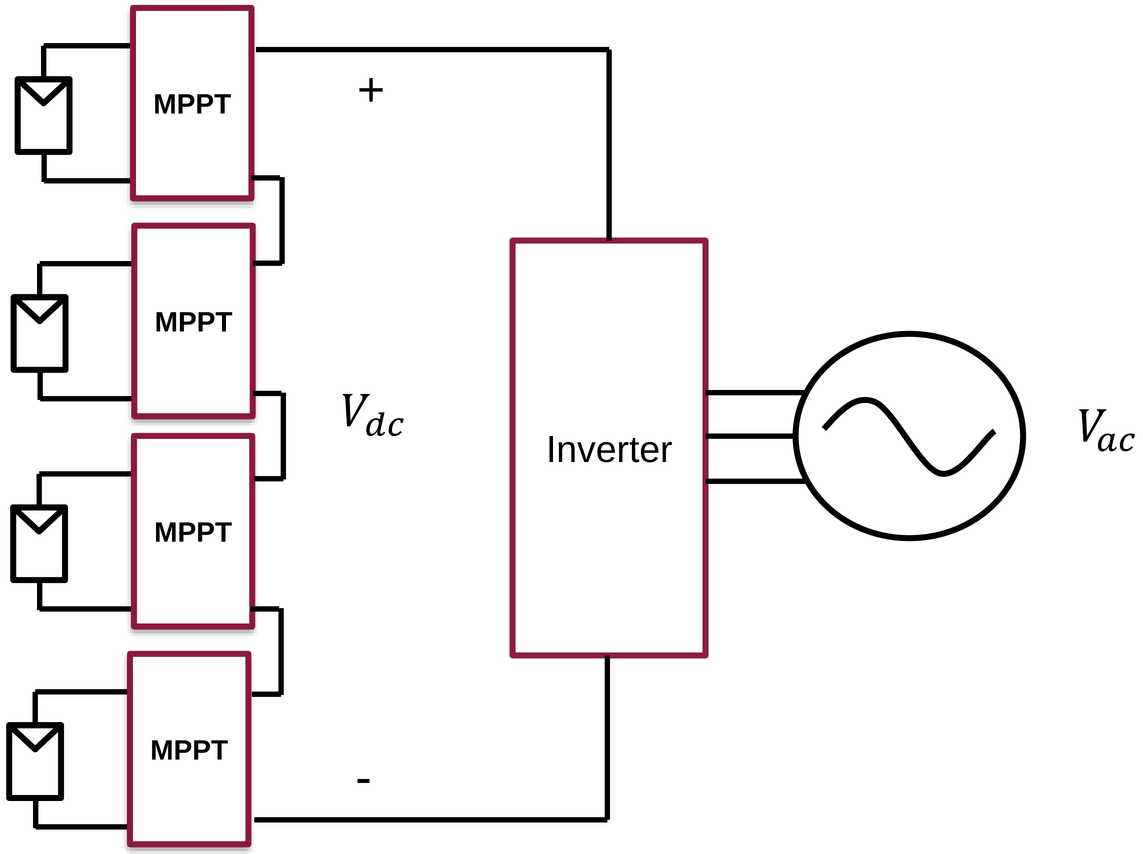
Module 4e

Grid-Forming Inverters – Energy Reserves, Transients, and Active Areas of Research

Energy Reserves are a Requirement

- All of these schemes <u>require</u> dispatchable power

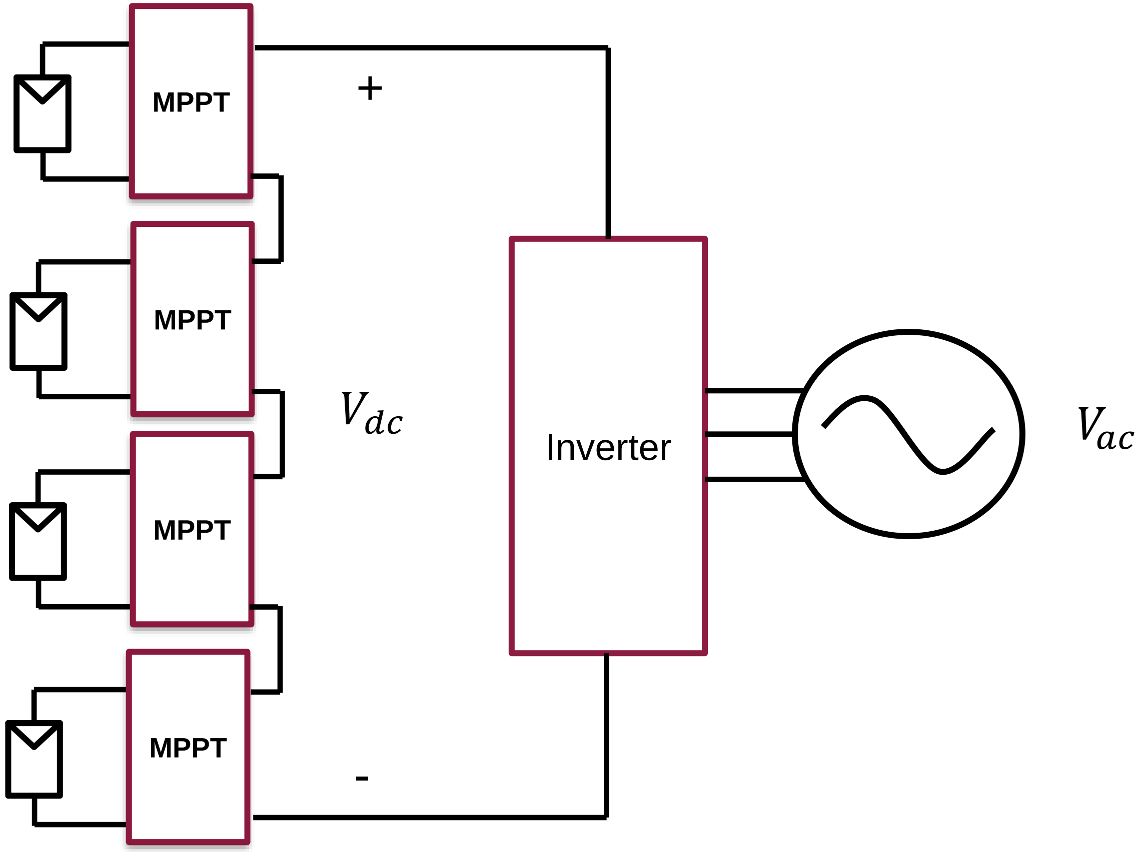




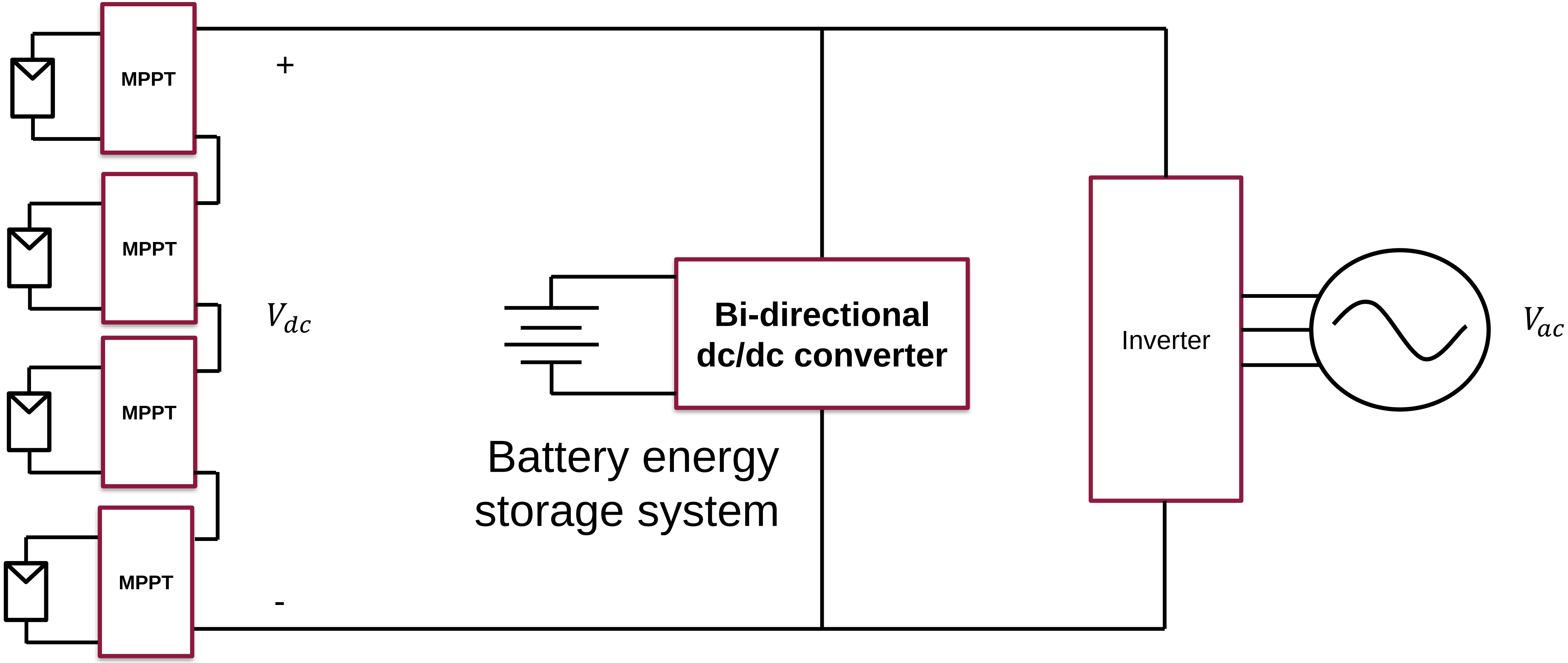
Renewable power isn’t dispatchable!

1. Purposefully Operate off Peak Power

- “De-rate” system to create headroom for increasing P
- Operate further off-peak to decrease P
- Not economic, wasting energy



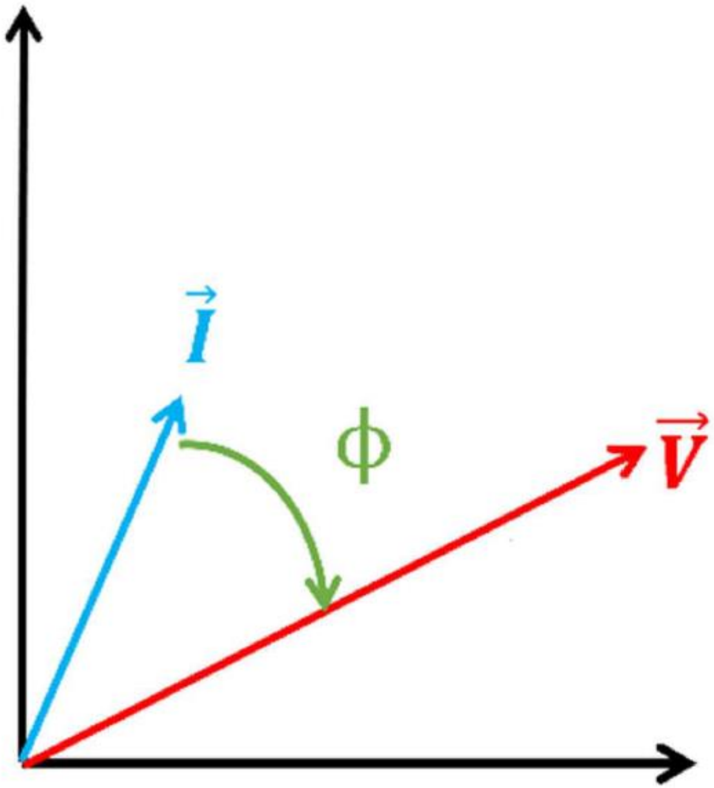
2. Integrate Energy Storage Systems



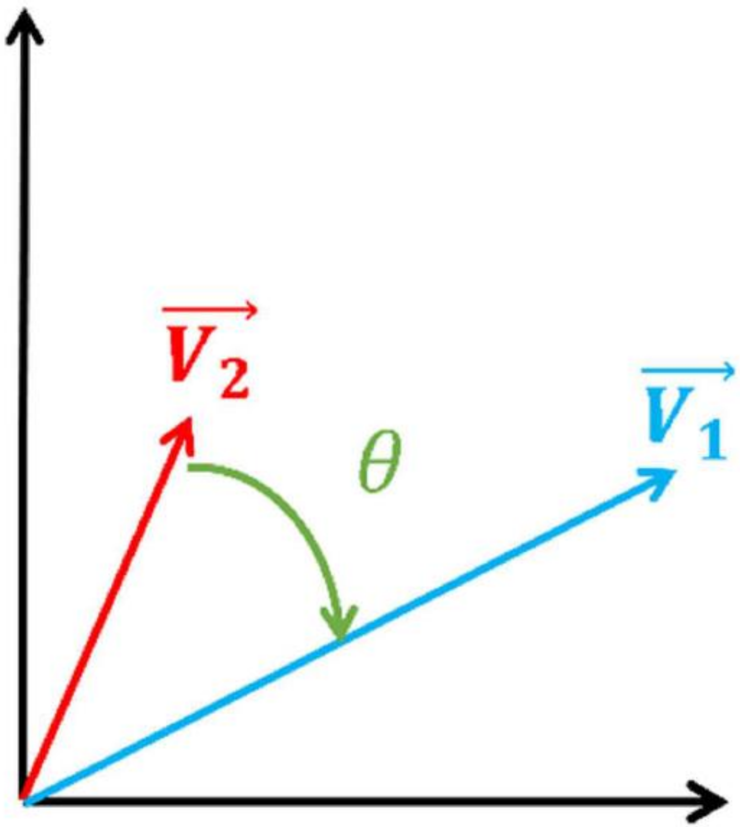
Transient Overload Capability

- During transients, currents higher than “nominal” (“rated”) may be demanded
- In synchronous machine, 6x overcurrent capability typical
- In inverters, more like 1.2x due to switch thermal inertia

Exasperated When Grid-Forming



Grid following, **I** regulated, no overcurrent with change in **V**

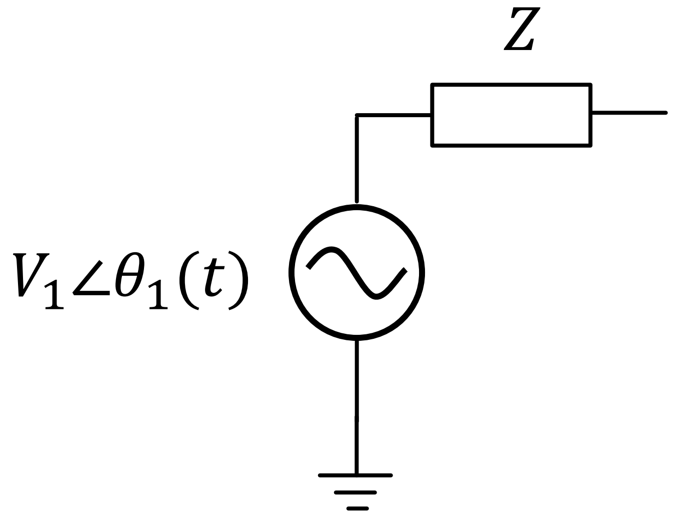


Grid forming, sudden change in grid voltage yields dramatic change in I

G. Denis, T. Prevost, M.-S. Debry, F. Xavier, X. Guillaud, and A. Menze, “The Migrate project: the challenges of operating a transmission grid with only inverter-based generation. A grid-forming control improvement with transient current-limiting control,” *IET Renewable Power Generation*, vol. 12, no. 5, pp. 523–529, 2018, doi: 10.1049/iet-rpg.2017.0369.

Correctable in Control

- “Threshold virtual impedance” (TVI) concept



- When current increases above threshold, modify control *as if* a larger impedance existed in series

- i.e. reduce voltage output by the inverter by Z_{virtual} times measured current

Short-circuit Capability

- Inverter needs to feed faults, but fault currents can easily damage switches.
- Don’t want to overrate switches, so SC response is carefully controlled
- Push maximum rms current into devices, but devices inherently rated for much less than what a machine can handle

X. Pei and Y. Kang, “Short-Circuit Fault Protection Strategy for High-Power Three-Phase Three-Wire Inverter,” *IEEE Transactions on Industrial Informatics*, vol. 8, no. 3, pp. 545–553, Aug. 2012, doi: 10.1109/TII.2012.2187913.

Y. Zhang, X. Pei, Z. Li, and P. Zhou, “Short-Circuit Current Limiting Control Strategy for Single-Phase Inverter Based on Adaptive Reference Feedforward and Third Harmonic Elimination,” *IEEE Transactions on Power Electronics*, vol. 37, no. 5, pp. 5320–5332, May 2022, doi: 10.1109/TPEL.2021.3133843.

Many Open Research Questions

1. Black-start, how do we bring the entire system online?
2. Experimental case studies of massively paralleled grid-forming IBRs
3. Interplay between IBRs and SMs