Design, Stability and Control of Ad Hoc Microgrids

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Microgrids in developed world


Increased reliability

Integration of DER

Microgrids in developing world

More than 1 billion people lack power access

Opportunity and demand for low cost autonomous microgrids

Ad Hoc Microgrids

- Modular sources/loads connected in an **ad hoc** fashion.
- Particularly suited to **off-grid** applications.
- Combine benefits of:
    1. Solar home systems
        - Ease of installation
        - No oversight required
        - Limited planning
    2. Conventional microgrids
        - Economies of scale
        - Expandable

Outline

- Ad hoc DC Microgrids (COMPEL ‘16 and CDC ‘16)
  - Challenges
  - Asymptotic stability
  - Secondary control
  - Transient stability
- AC microgrids (TPWRS ‘17 and CDC ‘17)
  - Droop control and stability
  - Local stability criteria
- Summary and Outlook

DC Grid: Challenges

The Challenge

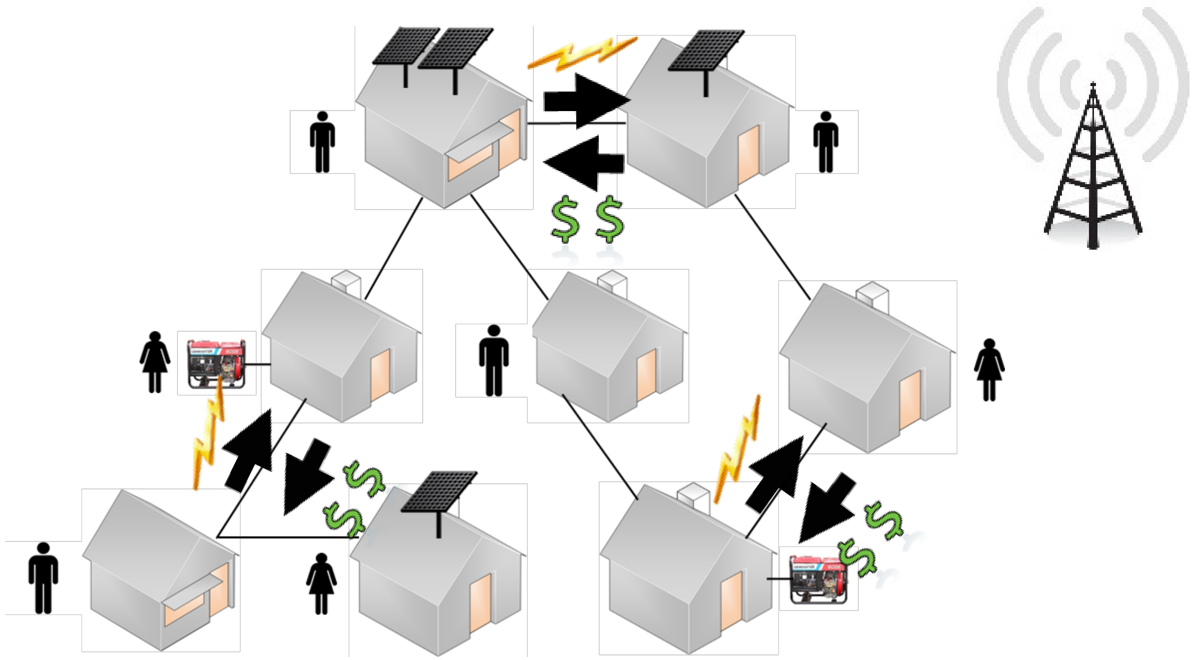
To design individual components (sources, loads, and lines) such that **any** network topology will function appropriately.

1. Stability:
   - Deriving “plug-and-play” criteria
2. Control:
   - Physically realizing a specified dispatch
   - Coordinating power converters
3. Optimal Dispatch/Real Time Pricing:
   - Inherently decentralized network
   - Large uncertainty about power supply/demand

Our Contribution

Our Ad Hoc Setting

Based on proposed LVDC (48V DC) architecture [1].



[1] "Architecture and system analysis of microgrids with peer-to-peer electricity sharing to create a marketplace which enables energy access," Inam et. al., ECCE-Asia 2015.

	Feature	Opportunity
1.	Entirely solar powered	Informs integration of renewables in large-scale grid.
2.	Power electronics at every node	Enables sophisticated algorithms (e.g., demand response).
3.	Designed for off-grid communities	Allows fast innovation because of limited incumbent infrastructure.

DC Grid: Asymptotic Stability

Overview

Structure

- **Goal:** existence, feasibility, and asymptotic stability of EQ point
- Strongly connected graph
- Nodes (sources, loads):
  - Total load power bounded by p_Σ
- Edges (lines):
  - Total line resistance bounded by R_Σ

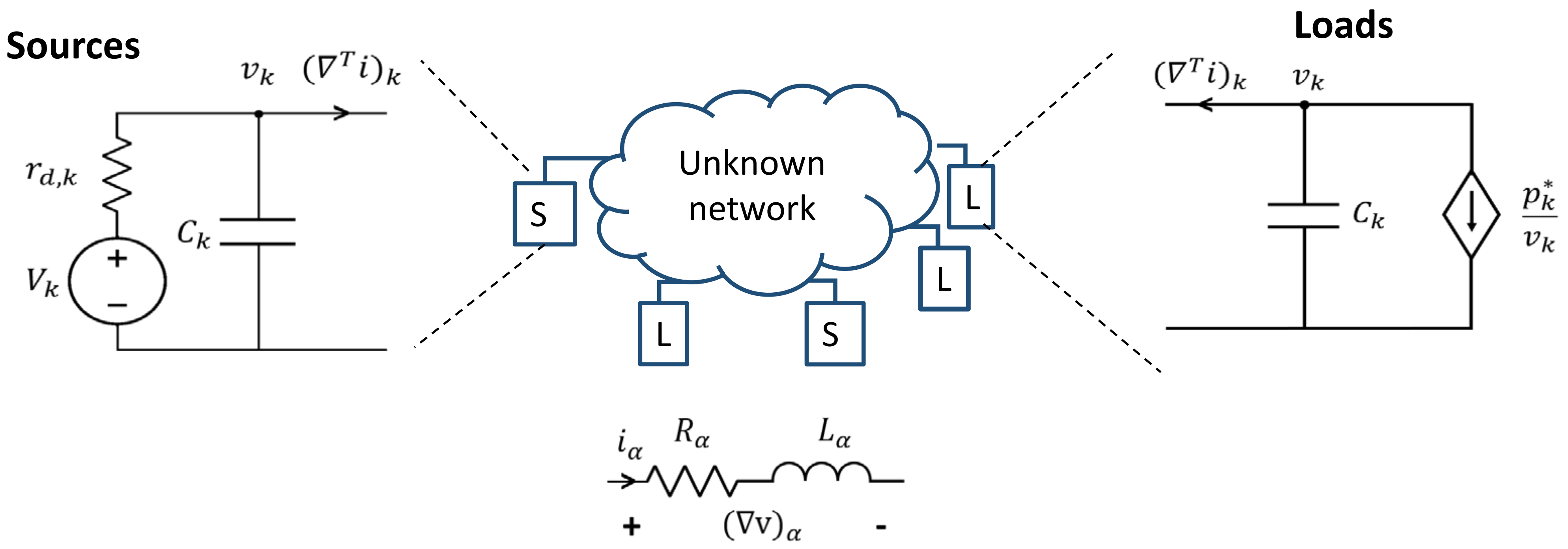
Results

- To transmit more total power, must reduce total resistance
- To draw more power at some node, must increase capacitance at that node.
  - ➢Size node capacitance for max power draw

Main Contribution

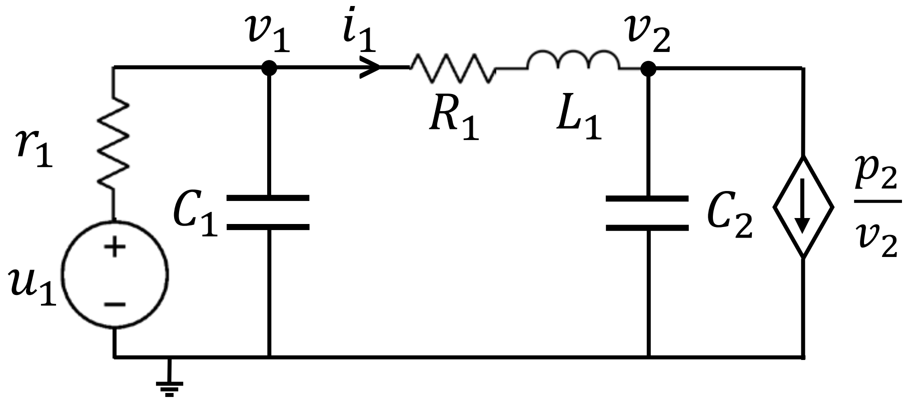
Source, Line, and Load Models

Constant Power Loads + Inductive Lines = Instability



Asymptotic Stability: State Equations

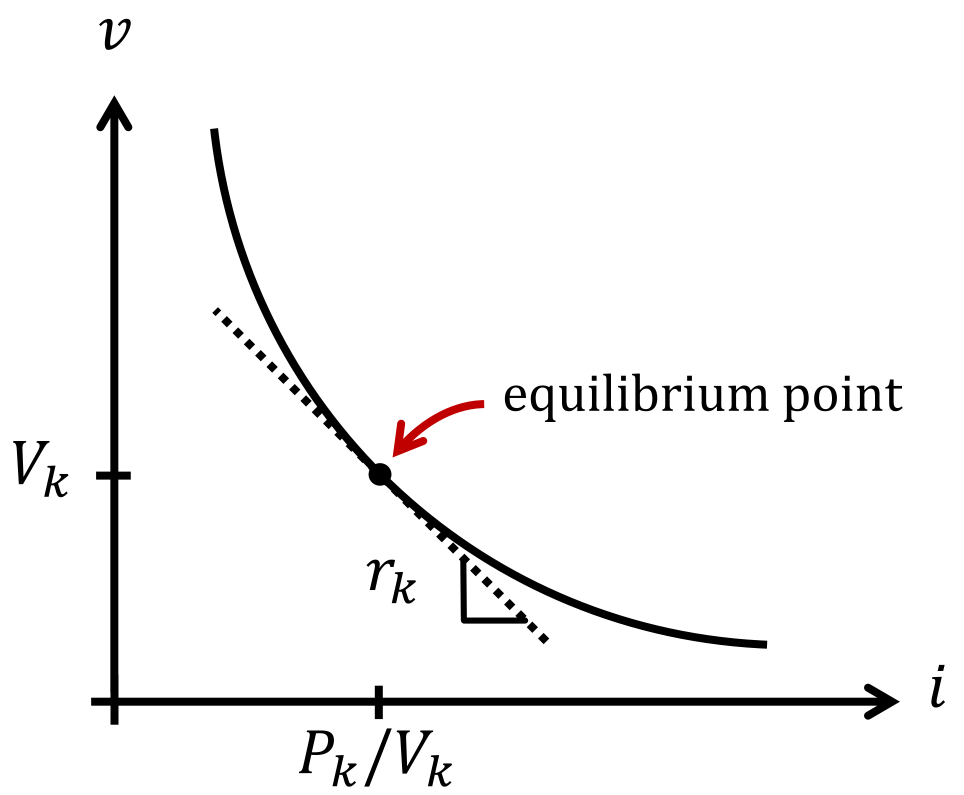
- KVL:
  - $L_1 \frac{di_1}{dt} + R_1 i_1 = v_1 - v_2 = \nabla v$
- KCL:
  - $C_1 \frac{dv_1}{dt} + \frac{v_1}{r_1} = -i_1 = -\nabla^{\mathrm{T}} i$
  - $C_2 \frac{dv_2}{dt} - \frac{p_2}{v_2} = i_1 = -\nabla^{\mathrm{T}} i$
- Controller:
  - $C_{u,1} \frac{du_1}{dt} = \frac{V_{ref} - v_1}{r_1}$



Simple network to illustrate setup.

Major Challenge: Constant Power Loads

- Caused by tightly-regulated power electronics
- “Negative resistance”
  - Not incrementally passive
  - -L/R, -RC, now in right half plane
- Can destabilize networks
  - EQ point may not exist
  - Network may not be asymptotically stable



Finding a Potential Function

- Can't use energy/passivity
  - Negative R injects power into the network
- Can use Brayton-Moser potential

1. $Q\dot{x} = -\frac{\partial}{\partial x}\mathcal{P}$
2. $\frac{\partial}{\partial t}\mathcal{P} < 0$ (decay)
3. $\frac{\partial^2}{\partial x^2}\mathcal{P} \succcurlyeq 0$ (convexity at EQ)

Brayton-Moser potential:

$$\mathcal{P} = \frac{\tau}{2}\left(\frac{dv}{dt}\right)^T C\left(\frac{dv}{dt}\right) + p^T \ln(v) + \frac{1}{2}(\nabla v)^T R^{-1}(\nabla v) + \frac{1}{2}v^T r_d^{-1} v - V^T v$$

$$\frac{d\mathcal{P}}{dt} = -\left(\frac{dv}{dt}\right)^T \left[C - \frac{p}{v^2}\right]\left(\frac{dv}{dt}\right) < 0$$

$$\frac{\partial^2\mathcal{P}}{\partial v^2} = \nabla^T R^{-1}\nabla + r_d^{-1} - \frac{p}{v^2} \succ 0$$

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Matrix Inequalities:

$$C - \frac{\tau_{max} p}{v^2} \succcurlyeq 0$$

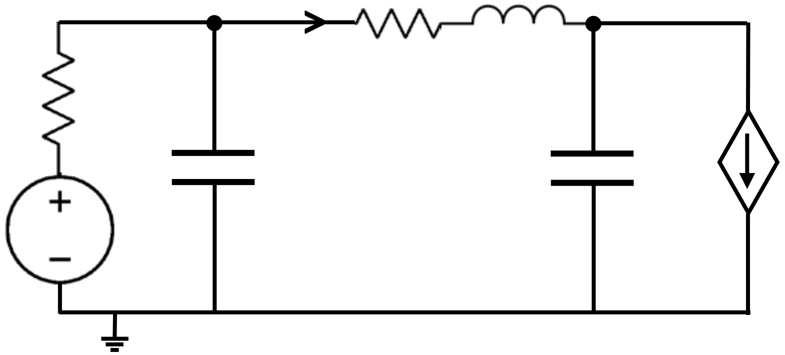
$$\nabla^T R^{-1} \nabla - \frac{p}{v^2} + r_d^{-1} \succcurlyeq 0$$

- $p_k \leq \frac{C_k V_{min}^2}{\tau_{max}}$ ∀ loads
- $p_\Sigma \leq \frac{V_{min}^2}{R_\Sigma + r_\kappa}$

	Result
EQ Point Existence	$p_\Sigma \leq \frac{V_{ref}^2}{4R_\Sigma}$
EQ Point Feasibility	$p_\Sigma \leq \frac{V_{min}(V_{ref} - V_{min})}{R_\Sigma}$
Asymptotic Stability	$p_k \leq \frac{c_k V_{min}^2}{\tau_{max}}$ ∀ loads, $p_\Sigma \leq \frac{V_{min}^2}{R_\Sigma + r_\kappa}$

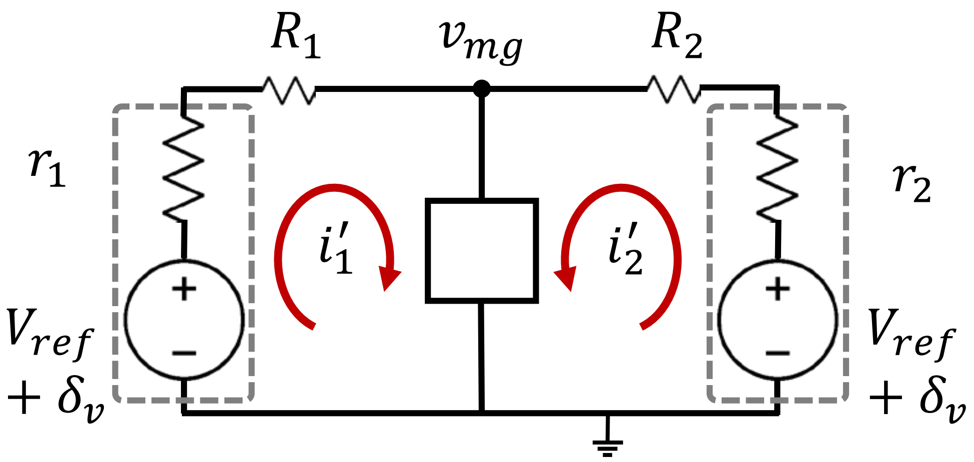
Interpretation: Worst-Case Topology

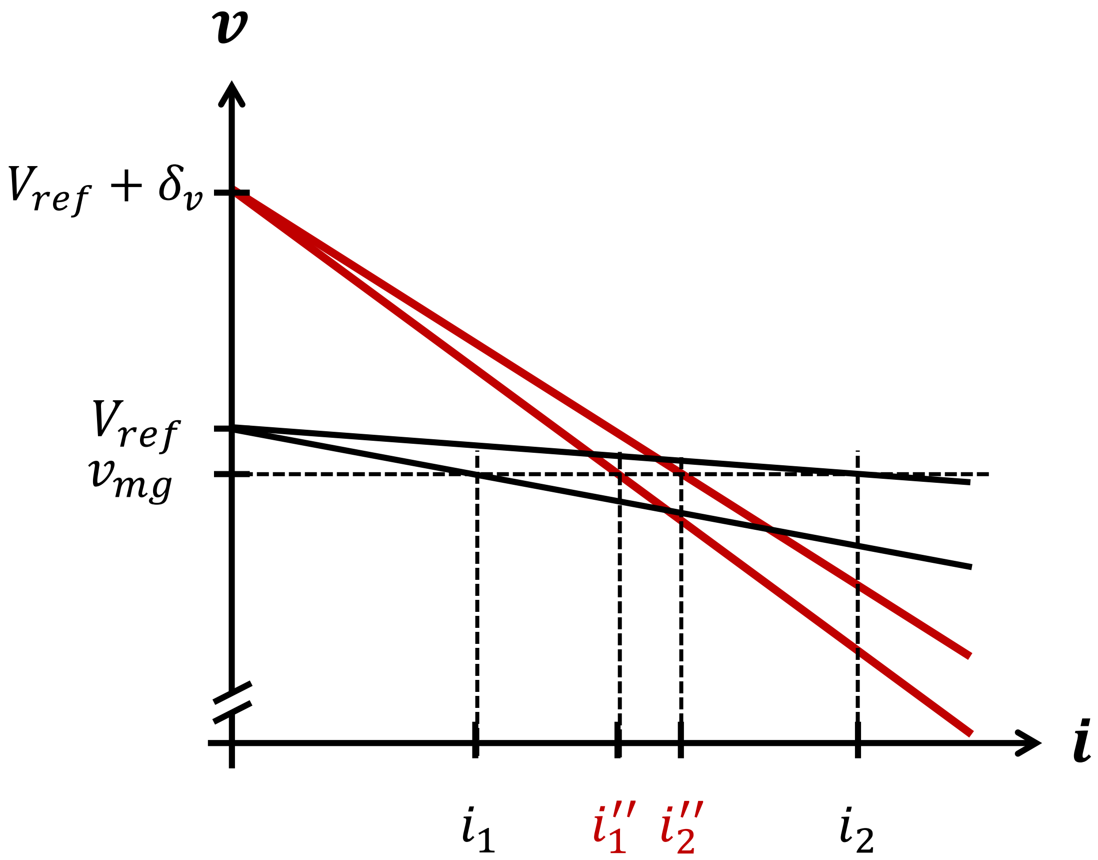
- Each stability condition is binding for the same, “worst-case,” topology.
- As a result, these conditions are both **necessary and sufficient** for ad hoc networks.



DC Grid: Secondary Control

Hierarchical Control

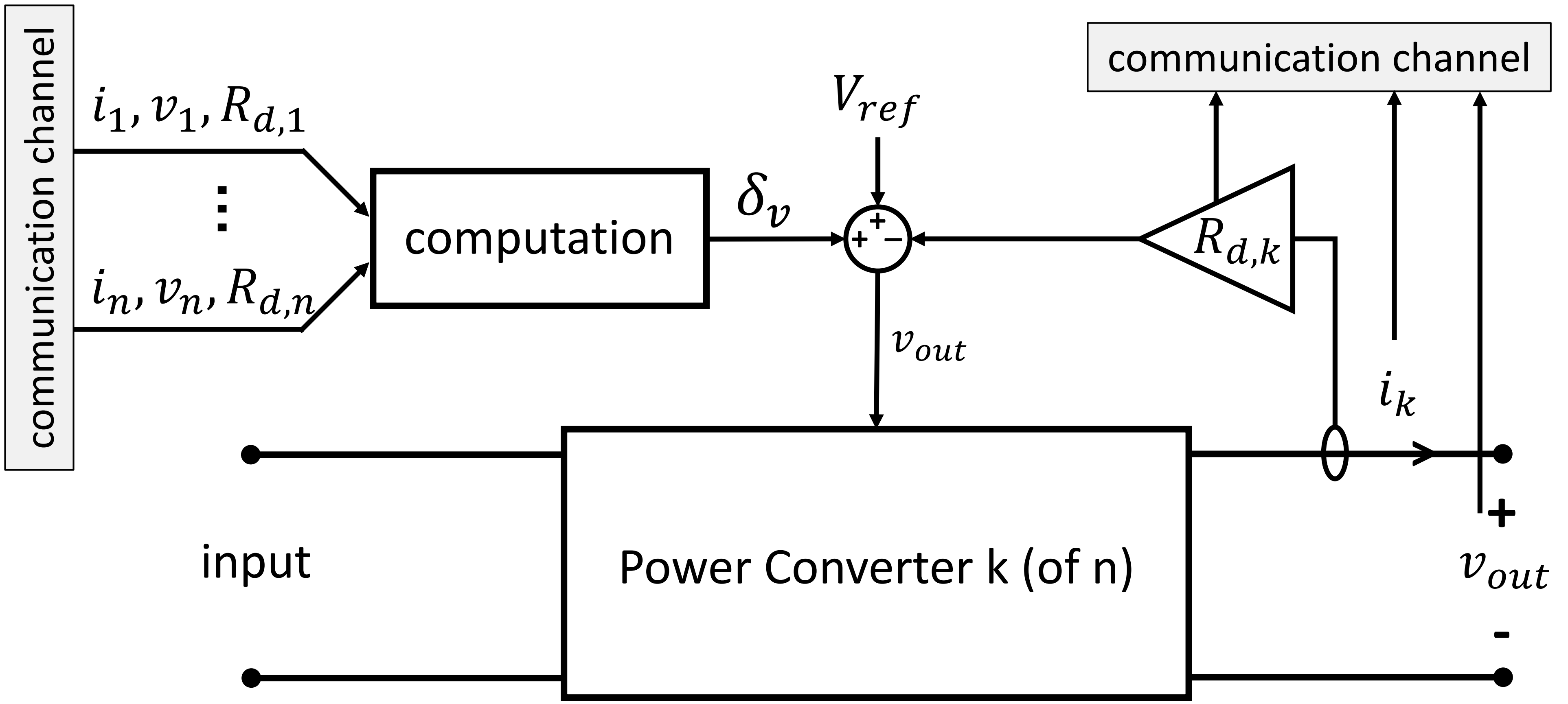




- **Limitation:** cannot support bidirectional sources (e.g., solar panel + battery).

"Distributed Control to Ensure Proportional Load Sharing and Improve Voltage Regulation in Low-Voltage DC Microgrids," J. Guerrero et. al.

Controller Implementation

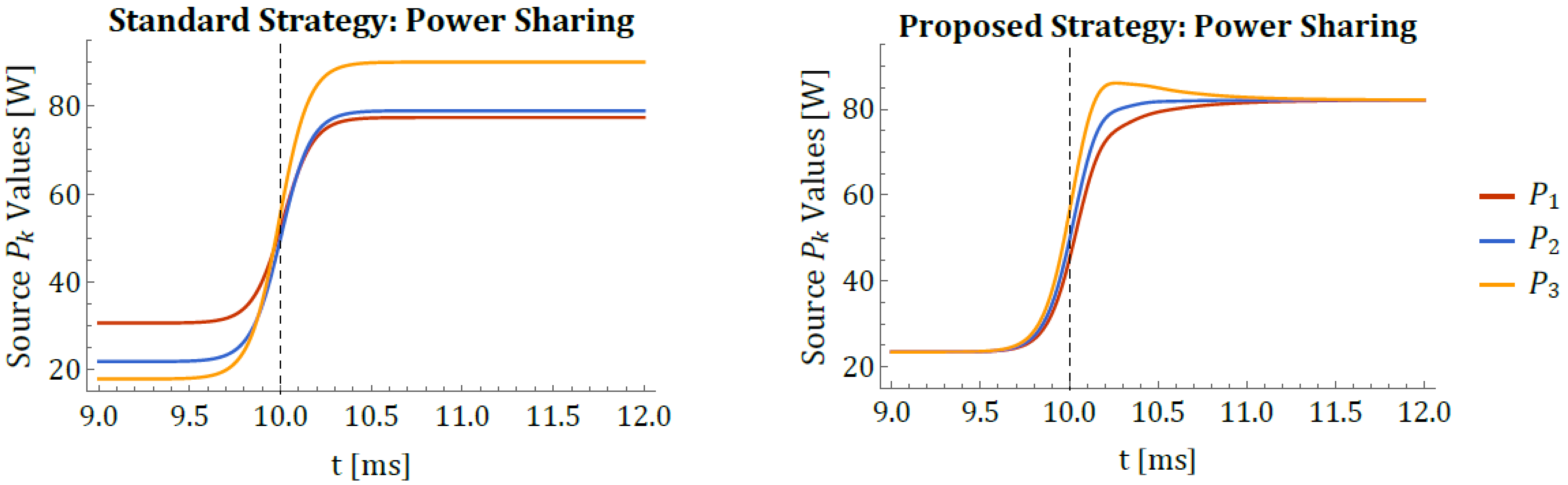


Our Method: Multipurpose Secondary Control

- Natively supports bidirectional sources
- Secondary Control: $\delta_v = k_p e + k_i \int_0^t e\, dt$
- $e = (V_{ref} - \bar{v}) + (\lambda_k \bar{p} - p_k)$ **Our Addition**

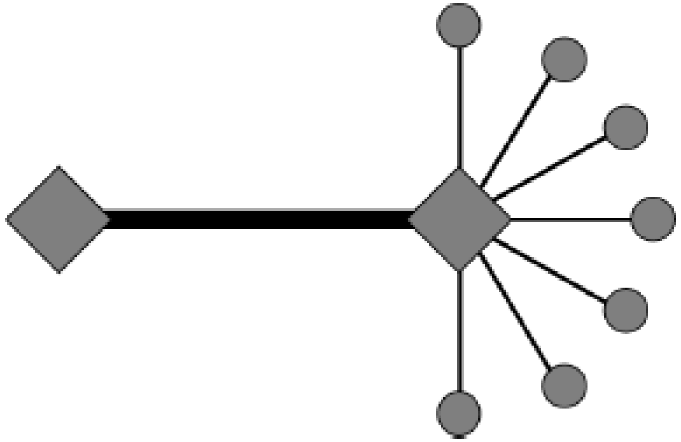
- λ_k is the participation factor of source k
- $\lambda_k < 0$: demanding power
- $\lambda_k > 0$: supplying power

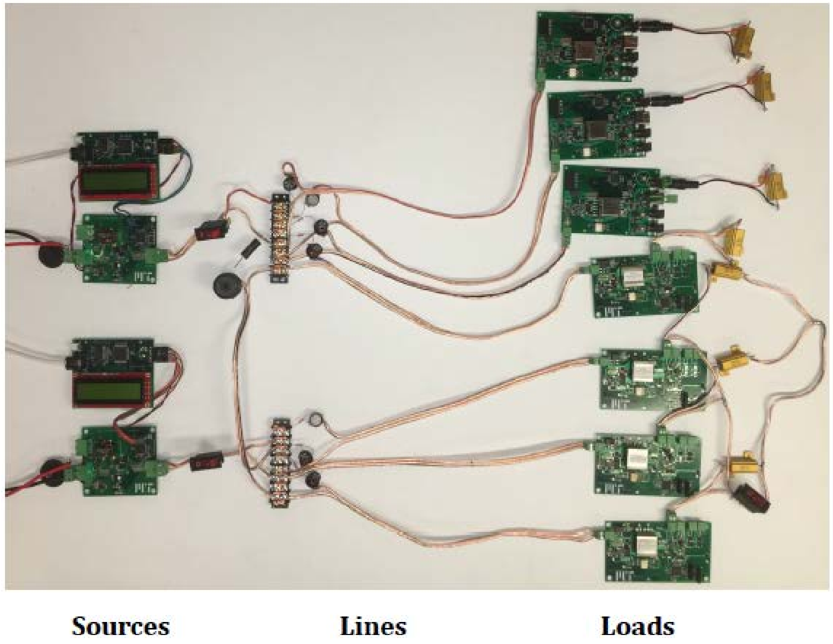
Simulated Comparison



Key Feature: our strategy allows different δ_v values for each source.

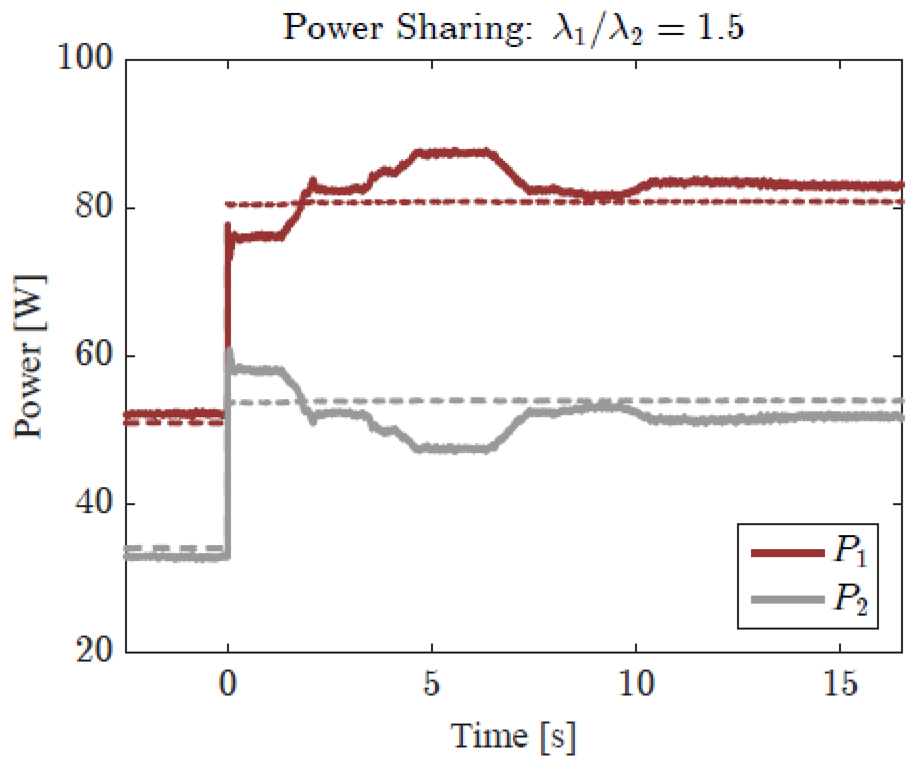
Experimental Setup

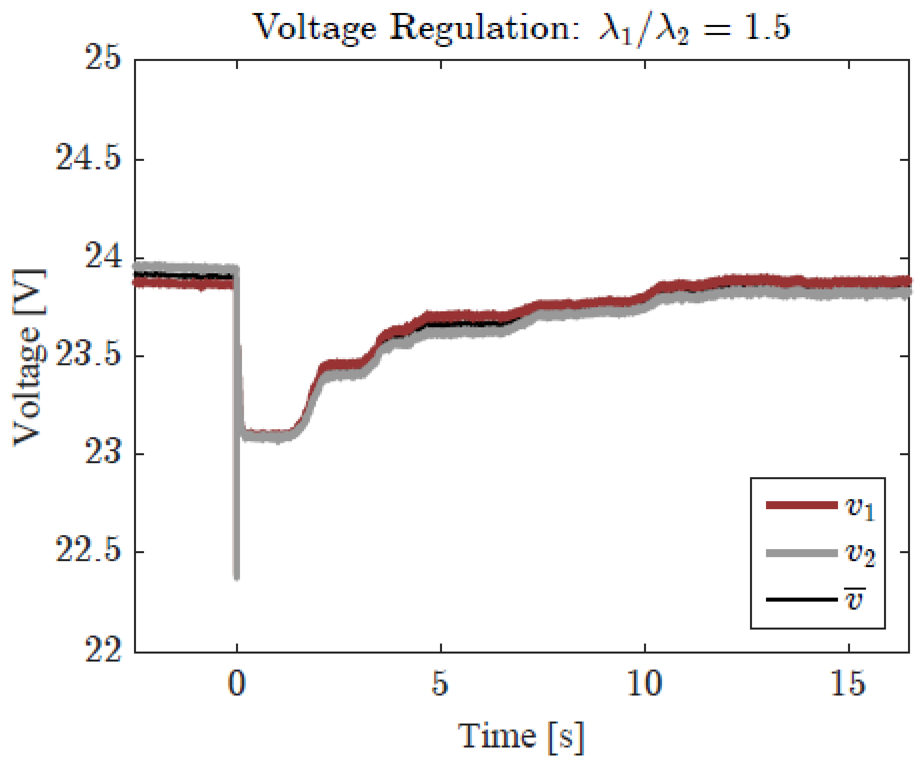




W. Inam, J. A. Belk, K. Turitsyn and D. J. Perreault, "Stability, control, and power flow in ad hoc DC microgrids," COMPEL 2016.

Experimental Results





W. Inam, J. A. Belk, K. Turitsyn and D. J. Perreault, "Stability, control, and power flow in ad hoc DC microgrids," COMPEL 2016.

DC Grid: Transient Stability

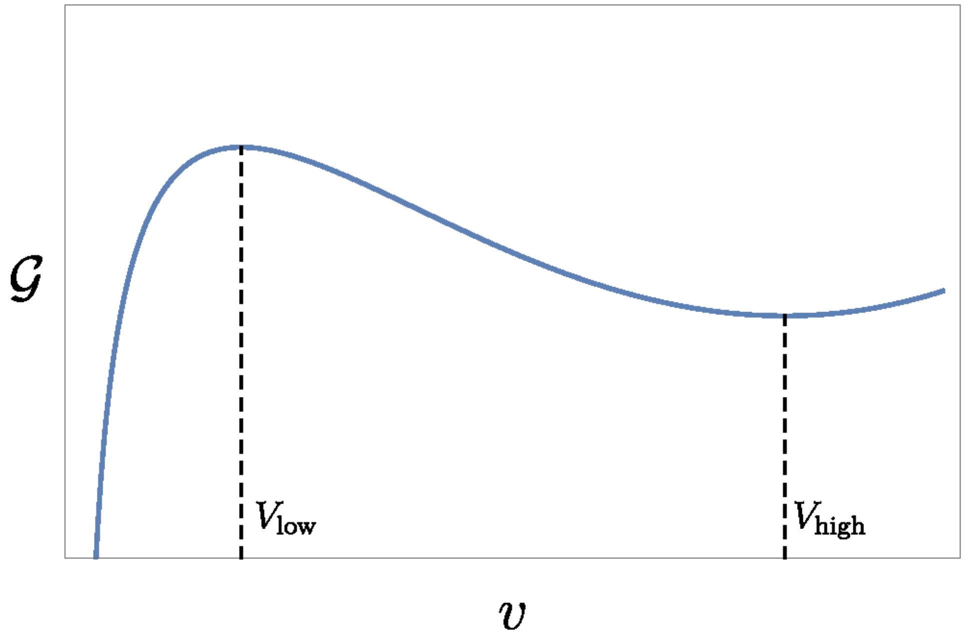
Transient stability problem

- **Problem**: single load switching events can cause heavy transients and potentially voltage collapse

- **Challenge**: find design constraints certifying stability under admissible switchings

Brayton-Moser potential:

$$\mathcal{P} = \frac{\tau}{2}\left(\frac{dv}{dt}\right)^T C\left(\frac{dv}{dt}\right) + \mathcal{G}(v)$$



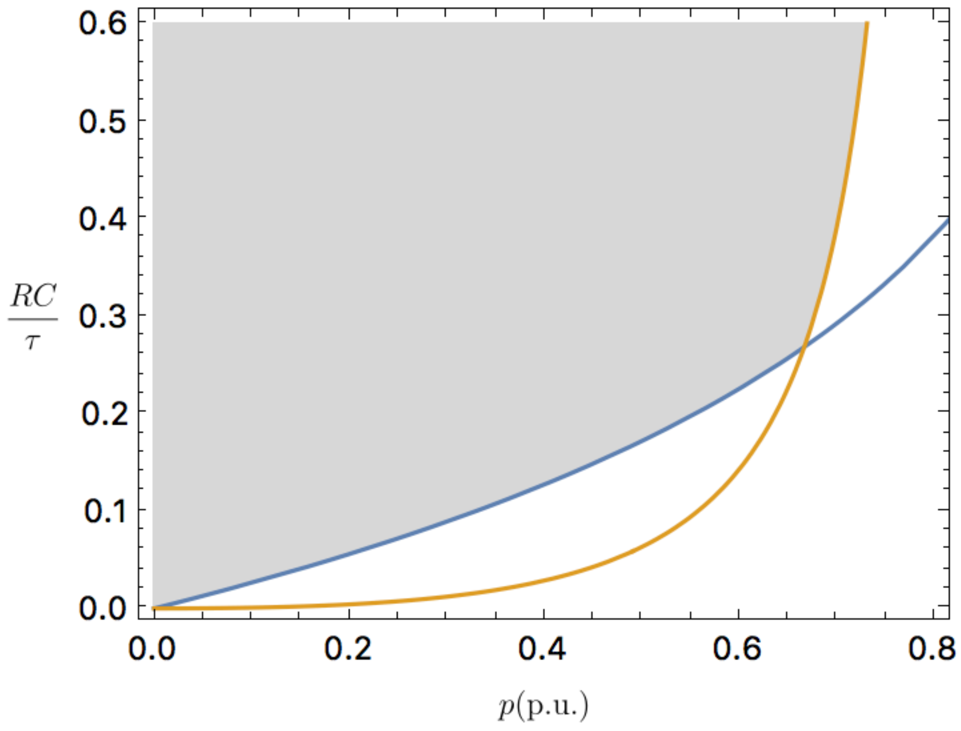
Certifying transient stability

Approach

1. Assume lowest acceptable transient voltage V_{tr}
2. Certify decay of $\mathcal{P}$ in $I = \{v: v_k > V_{tr}\}$ for **arbitrary** networks
3. Certify $\mathcal{P} > \mathcal{P}_{min}$ for any $v \in \partial I$ for **arbitrary** networks
4. Certify $\mathcal{P}(t+0) > \mathcal{P}_{min}$ after admissible switching events

Resulting criteria

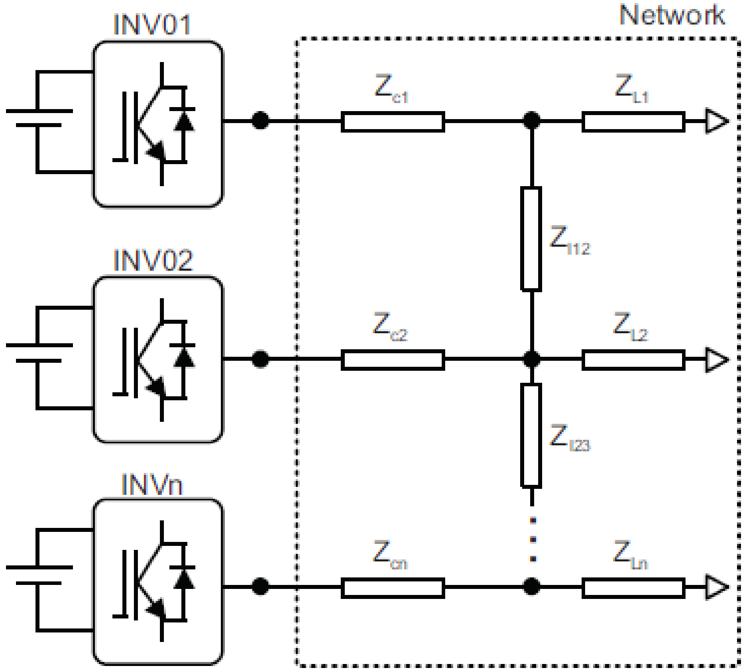
- No closed form expression for design constraints
- Family of designs, trade-offs between:
  - Capacitance values
  - Network utilization
  - Network Losses
- Resulting conditions only sufficient
- Asymptotic stability constraints are also necessary and bound conservativeness of transient one



AC Inverter based microgrids

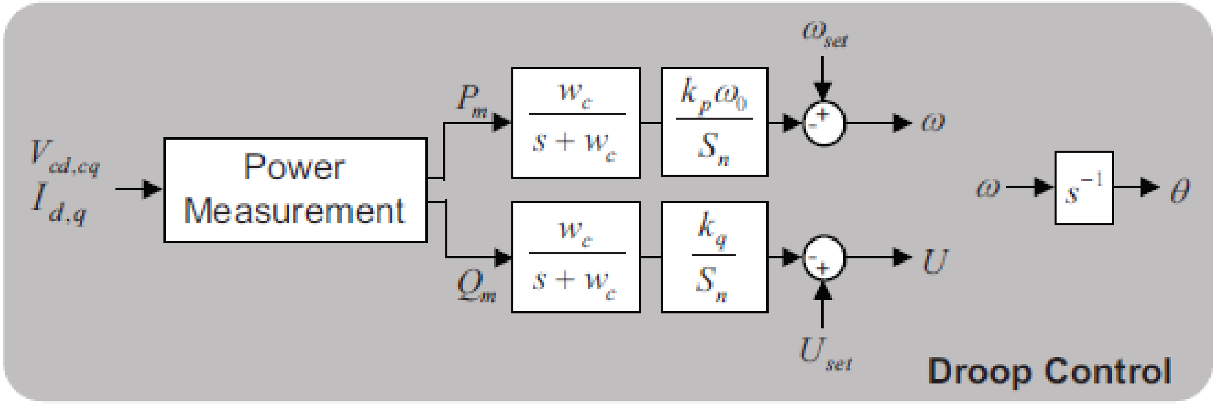
AC microgrid model

- 10 kVa base inverters connected in parallel
- Only resistive/inductive loads (for now)
- Low voltage microgrid 400V
- Small distances between inverters (<5km)
- Distribution grid: $X/R \approx 0.6$



Droop controls

- All inverters act as controllable voltage sources
- Droop control on voltage and frequency
- Shared responsibility in power balancing and voltage support
- Similar to generators, but:
  - Low inertia: $\tau \approx 30\ ms$
  - Low coupling impedance

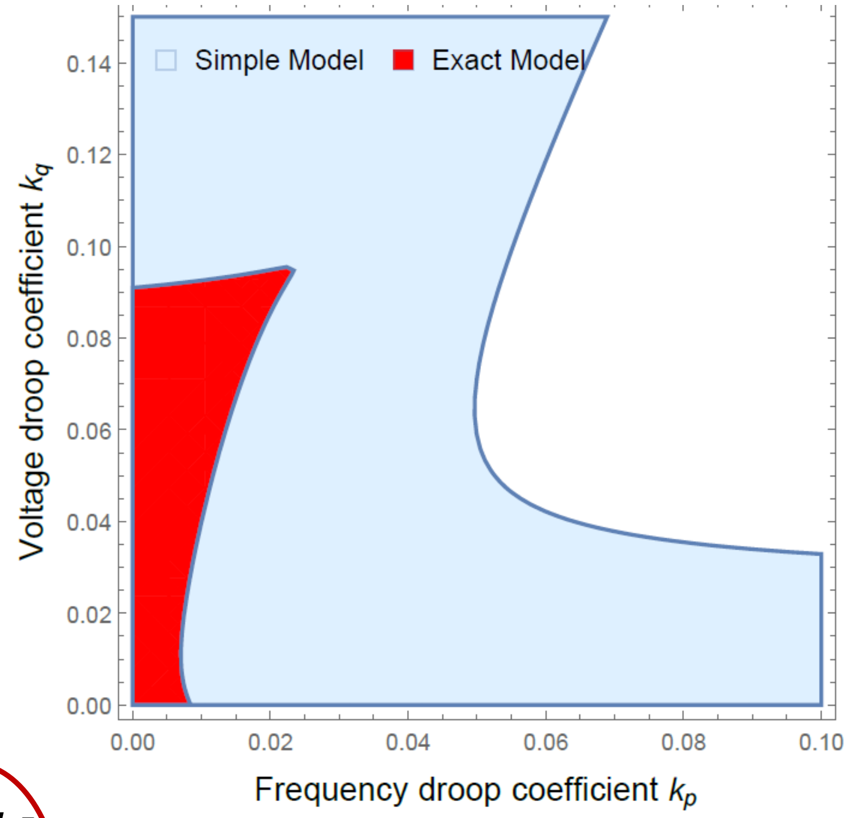


$$\tau \frac{d\omega}{dt} = \omega^\star - n_p P - \omega$$

$$\tau \frac{dU}{dt} = U^\star - n_q Q - U$$

Network delays

- Very short electromagnetic delays in lines: $L/R \approx 2\,ms$
- Typically ignored in control community papers
- Dramatically affects the stability boundary
- Limits the droops at realistic values, despite being passive energy-wise



$$L\frac{dI}{dt} = V_1 - V_2 - (R + j\omega_0 L)I$$

Interpretation

- Effective gains are very high:
  - Small voltage variations lead to huge variations of line current
  - Dynamic line ratings much higher than inverter ones
  - **Short/strong lines are bad for stability**
- Distribution grid acts almost like a single bus with multiple voltage sources attached
- High coupling impedance can solve the problem, but is expensive and hard to emulate

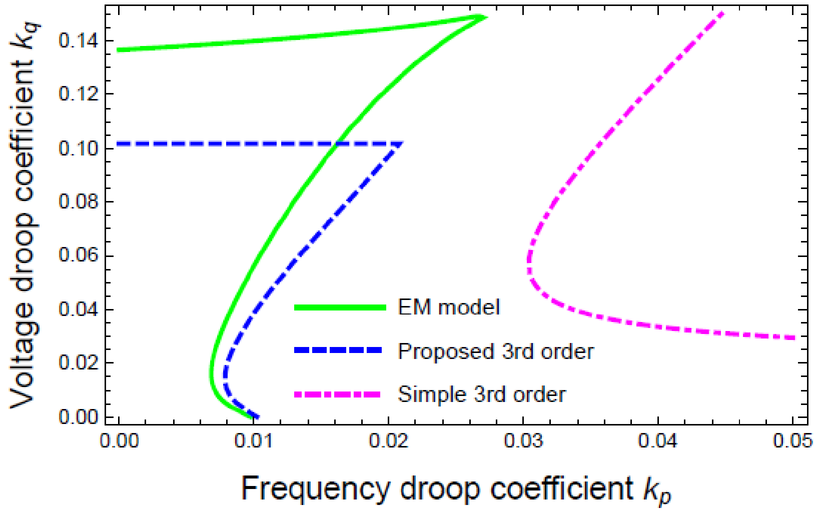
$$\tau \frac{d\omega}{dt} = \omega^\star - n_p P - \omega$$

$$\frac{k_p \omega_0}{S_0} \times \frac{L}{R} \times \frac{U_0^2 X R^2}{(X^2 + R^2)^2} \sim 1$$

$$k_p \times \frac{U_0^2}{R S_0} \times f(X/R) \sim 1$$

Improved modeling

- Systematic singular perturbation theory applied to the system
- Eliminate electromagnetic degrees of freedom while incorporating effect of delays
- Reasonable predictions of stability boundaries
- Asymptotically correct for $\frac{L}{R} \to 0$
- Strictly better than the popular swing equation models

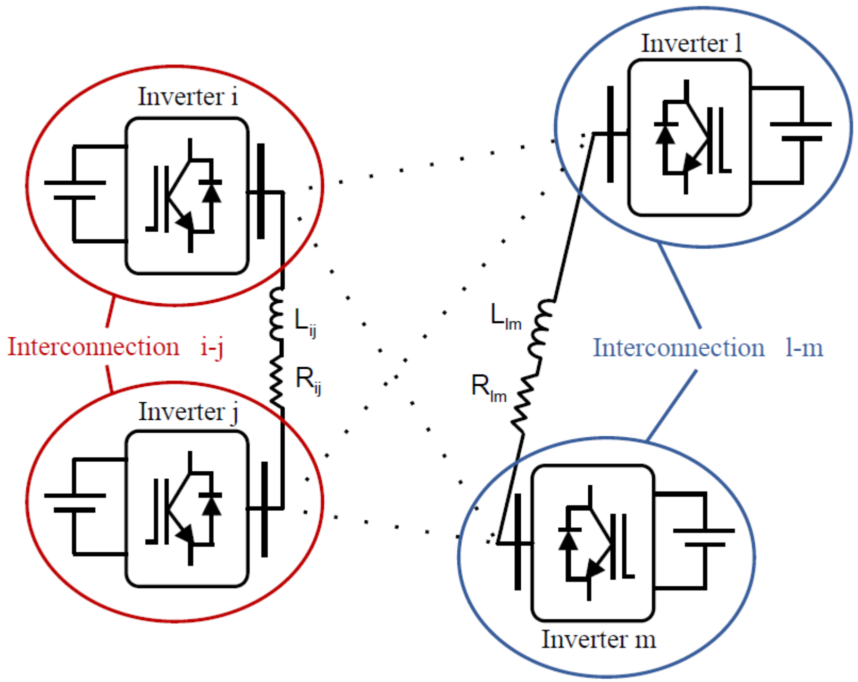


$$I(\omega) = Y(\omega)V(\omega)$$

$$I(t) = Y(\omega_0)V(t) - jY'(\omega_0)\frac{dV}{dt}$$

Towards ad hoc AC microgrids

- Simple local criteria certifying stability
- Linear constraints on droops depending only on neighbors
- Sufficient but not necessary
- Stability constrained:
  - Planning
  - Expansion
  - Reconfiguration
  - Droop (re)allocation



$$\frac{k_{pl}n_l}{S_l} + \frac{k_{pm}n_m}{S_m} < \frac{1}{U_0^2}\frac{(R_{lm}^{\;2}+X_{lm}^{\;2})^2}{4R_{lm}X_{lm}^{\;2}};$$

$$\frac{k_{ql}n_l}{S_l} + \frac{k_{qm}n_m}{S_m} < \frac{1}{U_0^2}\frac{X_{lm}(R_{lm}^{\;2}+X_{lm}^{\;2})}{2R_{lm}^{\;2}}$$

Towards ad hoc AC microgrids

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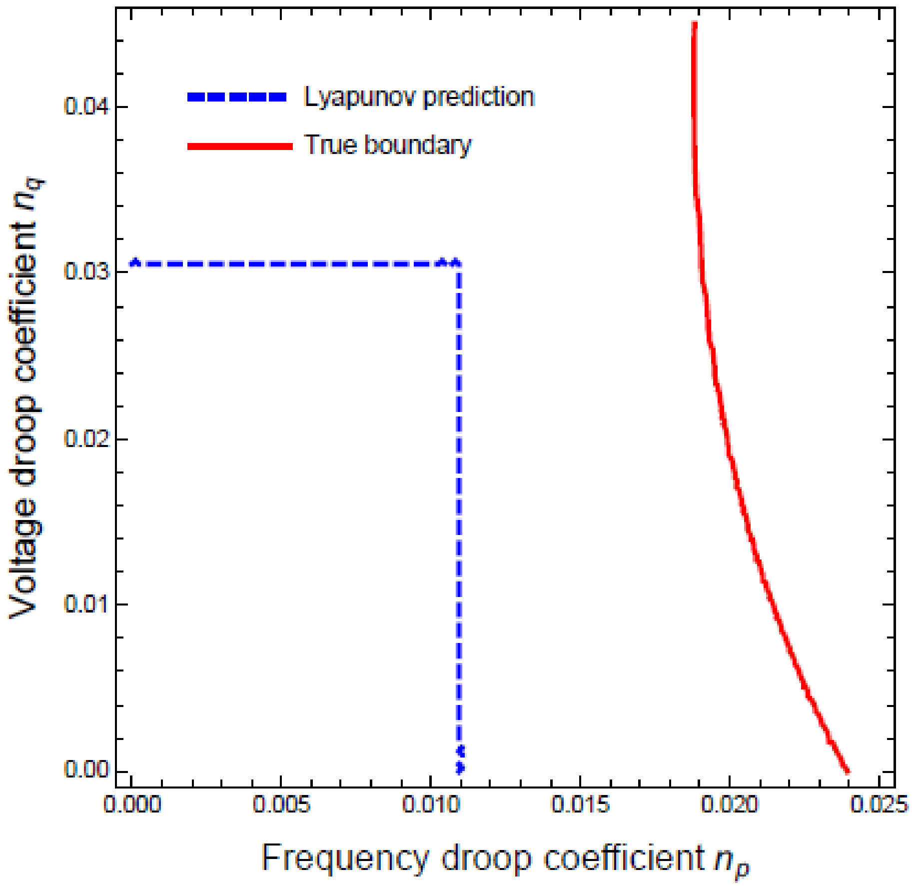

Summary and Outlook

Summary:

- Microgrids prone to stability
  - Inductive delays
  - Negative resistances
- Ad hoc microgrids:
  - Low cost
  - No oversight and central control
  - Easy expansion
  - Stable for arbitrary networks

Open problems:

- Extension to more general control loops
- Constraints for higher level controls



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