UNIVERSITY OF MINNESOTA

Grid-forming Power Electronics for Low-inertia Power Systems

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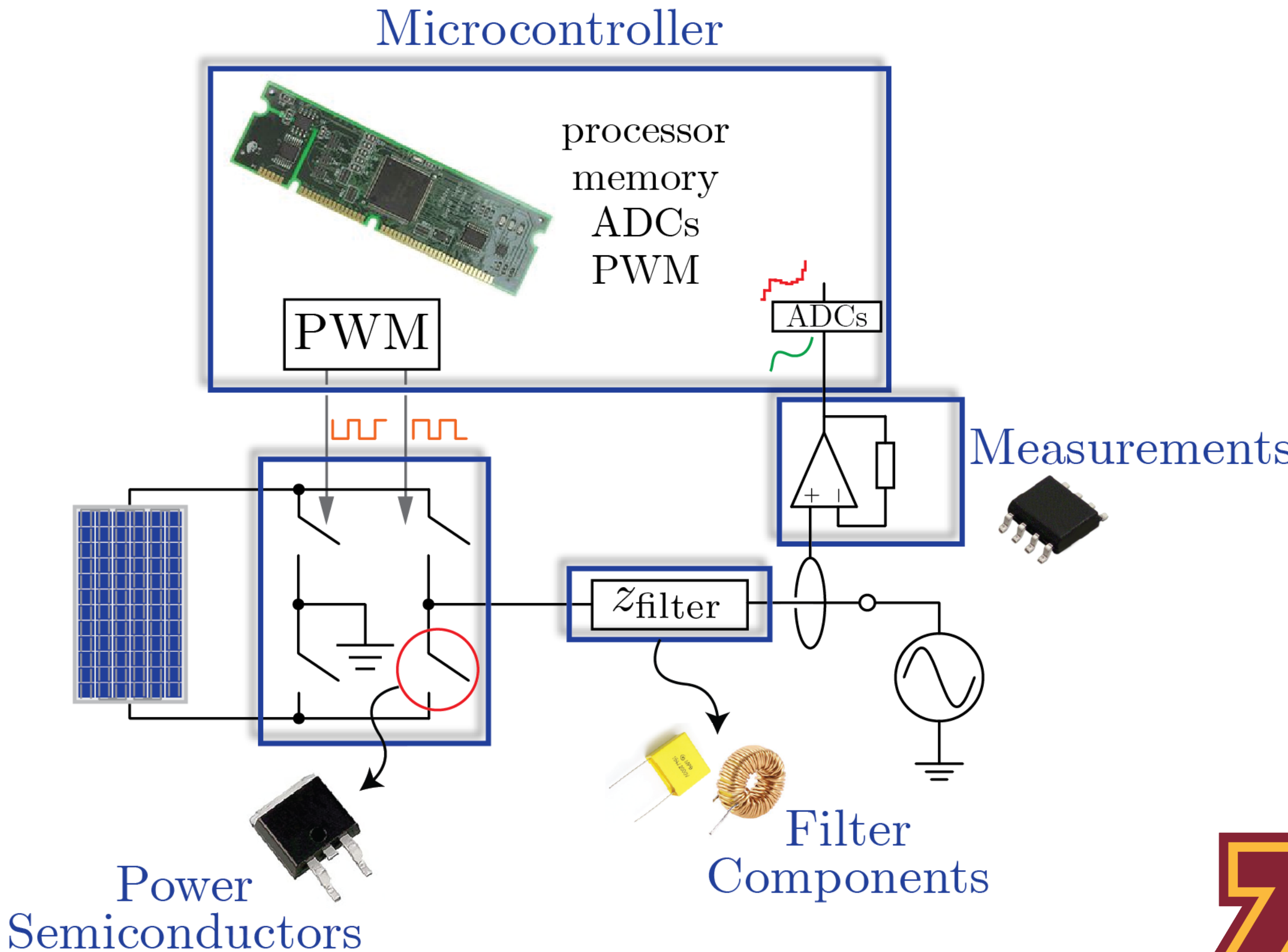
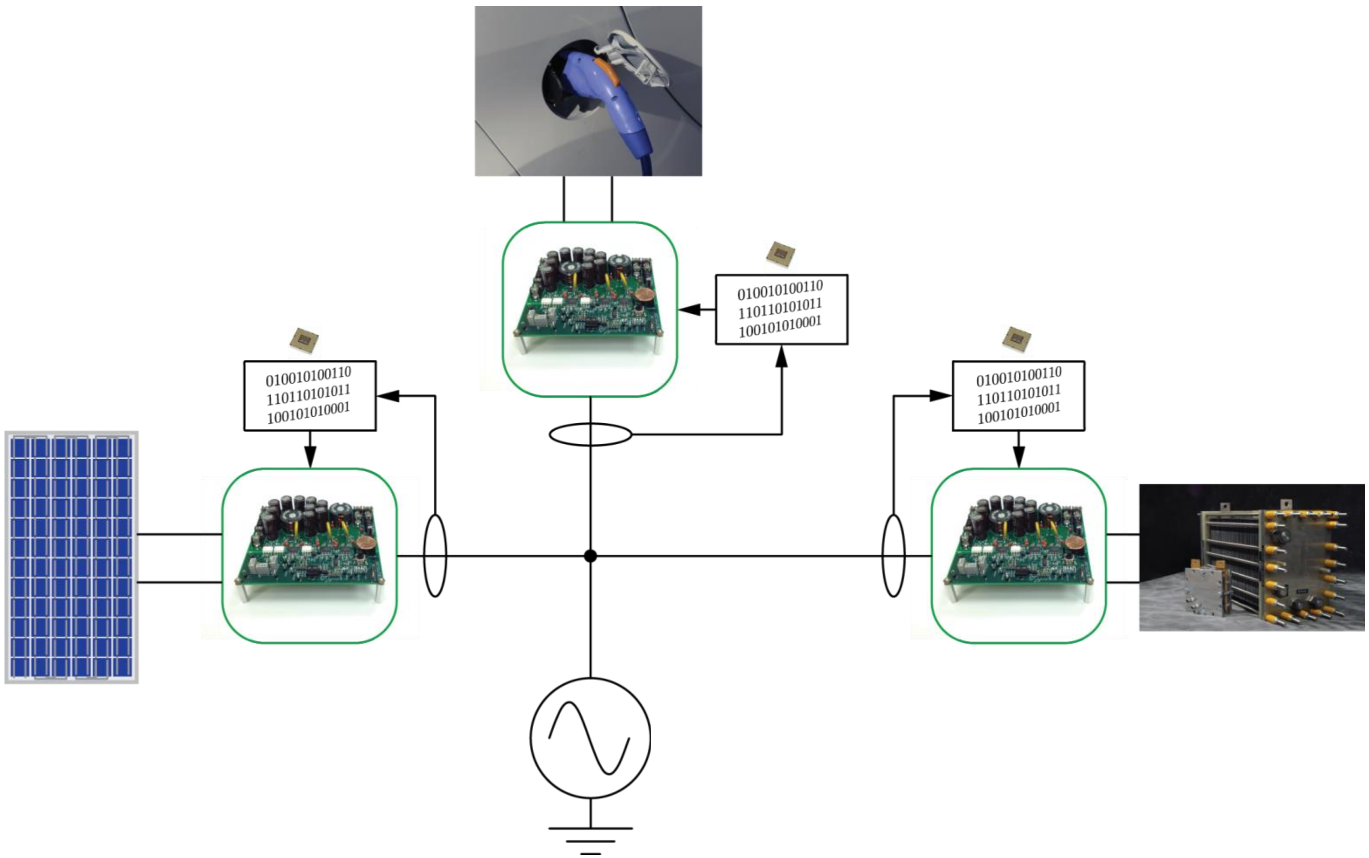
Building Block

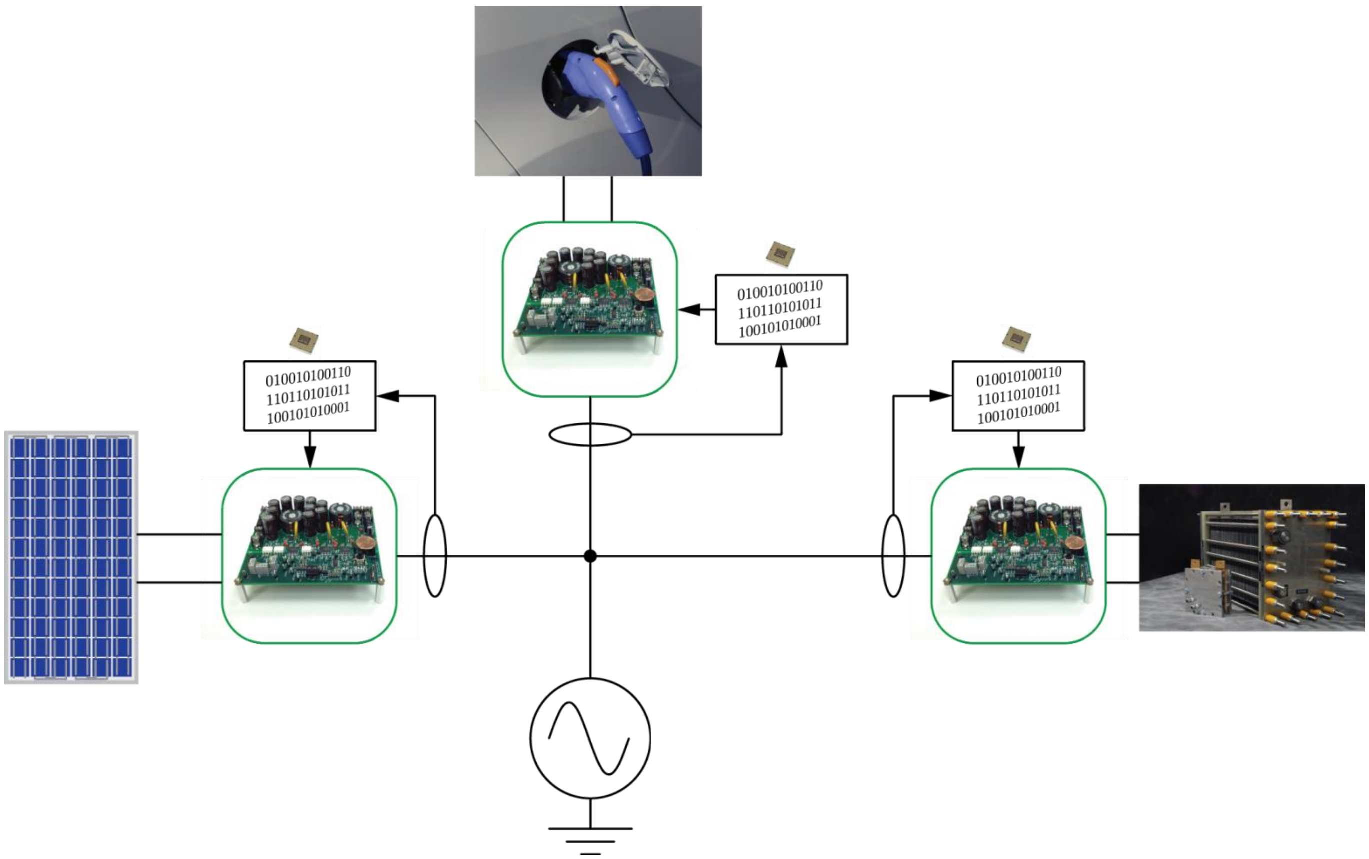


System Architecture



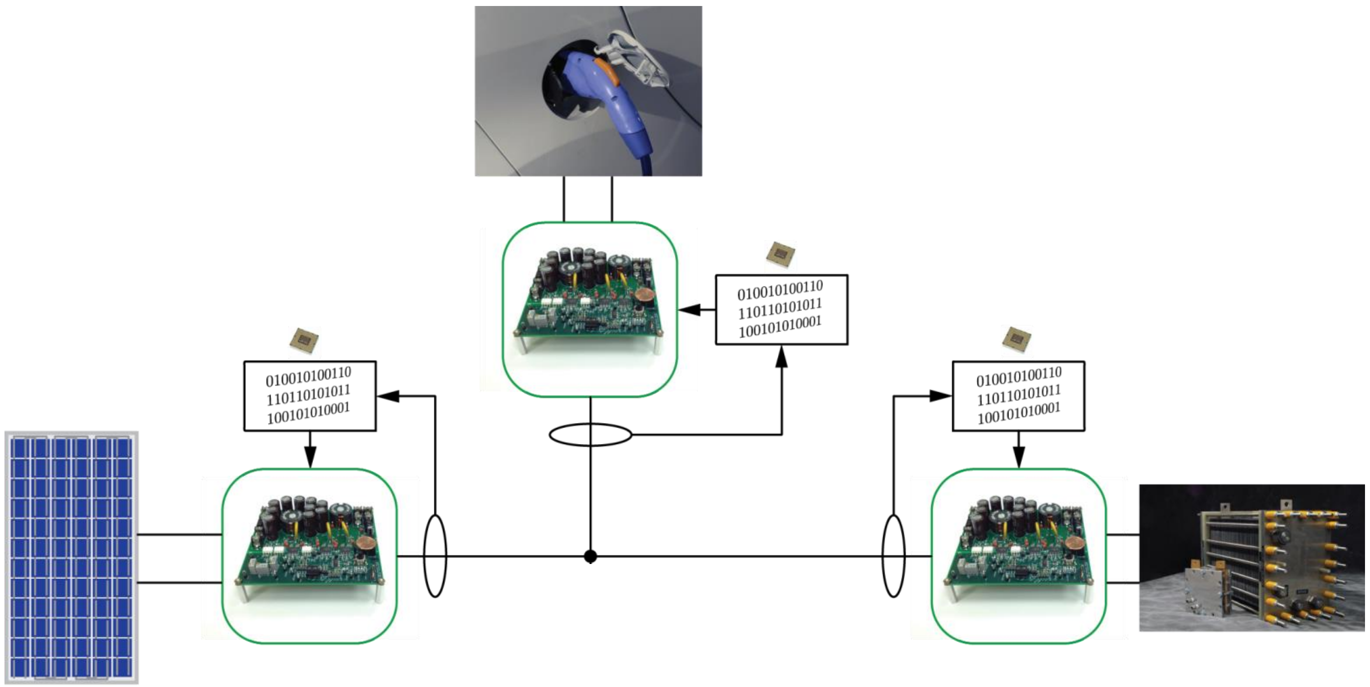
- Heterogeneous DC energy resources
- Semiconductor-based energy conversion
- High-bandwidth digital control

Challenges



- Variability, volatile dynamics
- Minimize communication, plug-and-play operation
- Low-to-no inertia

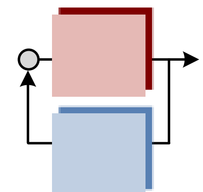
Challenges

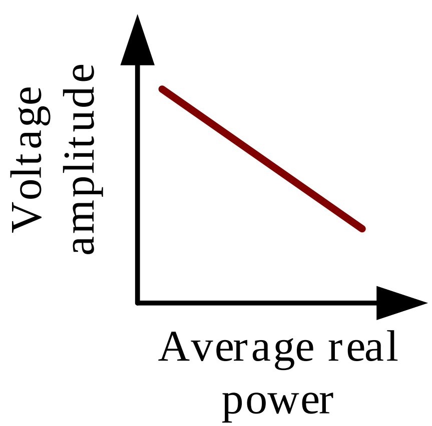


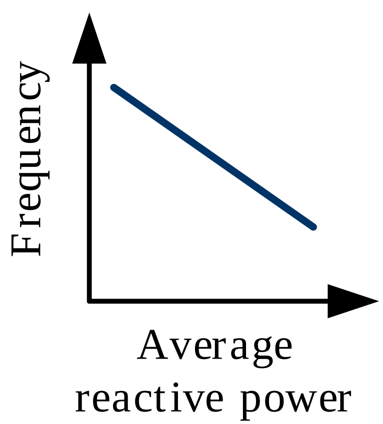
- Variability, volatile dynamics
- Minimize communication, plug-and-play operation
- Low-to-no inertia

State of the Art

- Droop Control[1]-[2]
- Inverters mimic synchronous machines
- Limitations
  - Assumes sinusoidal steady state
  - Slow dynamics
  - Hierarchical control



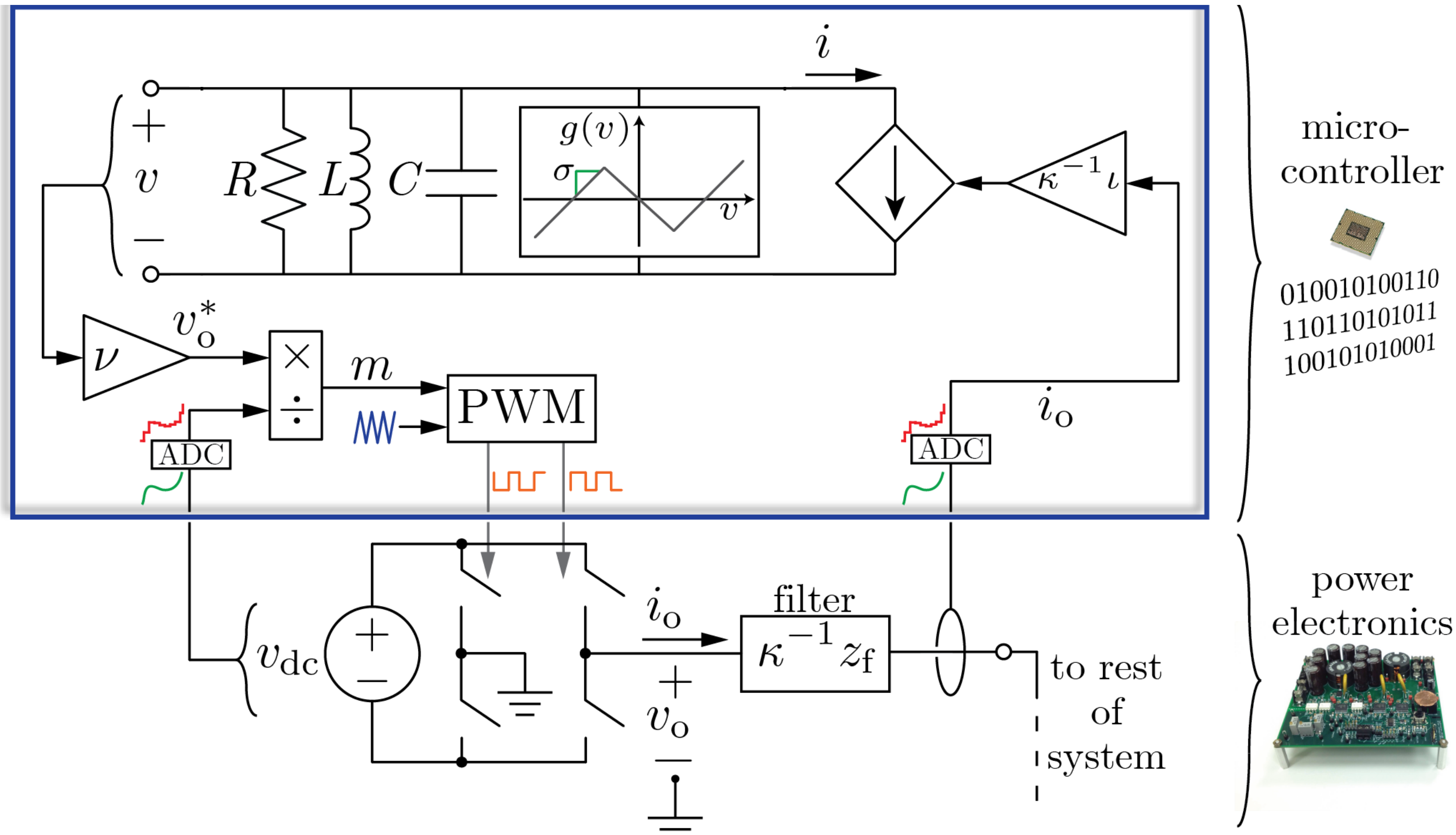




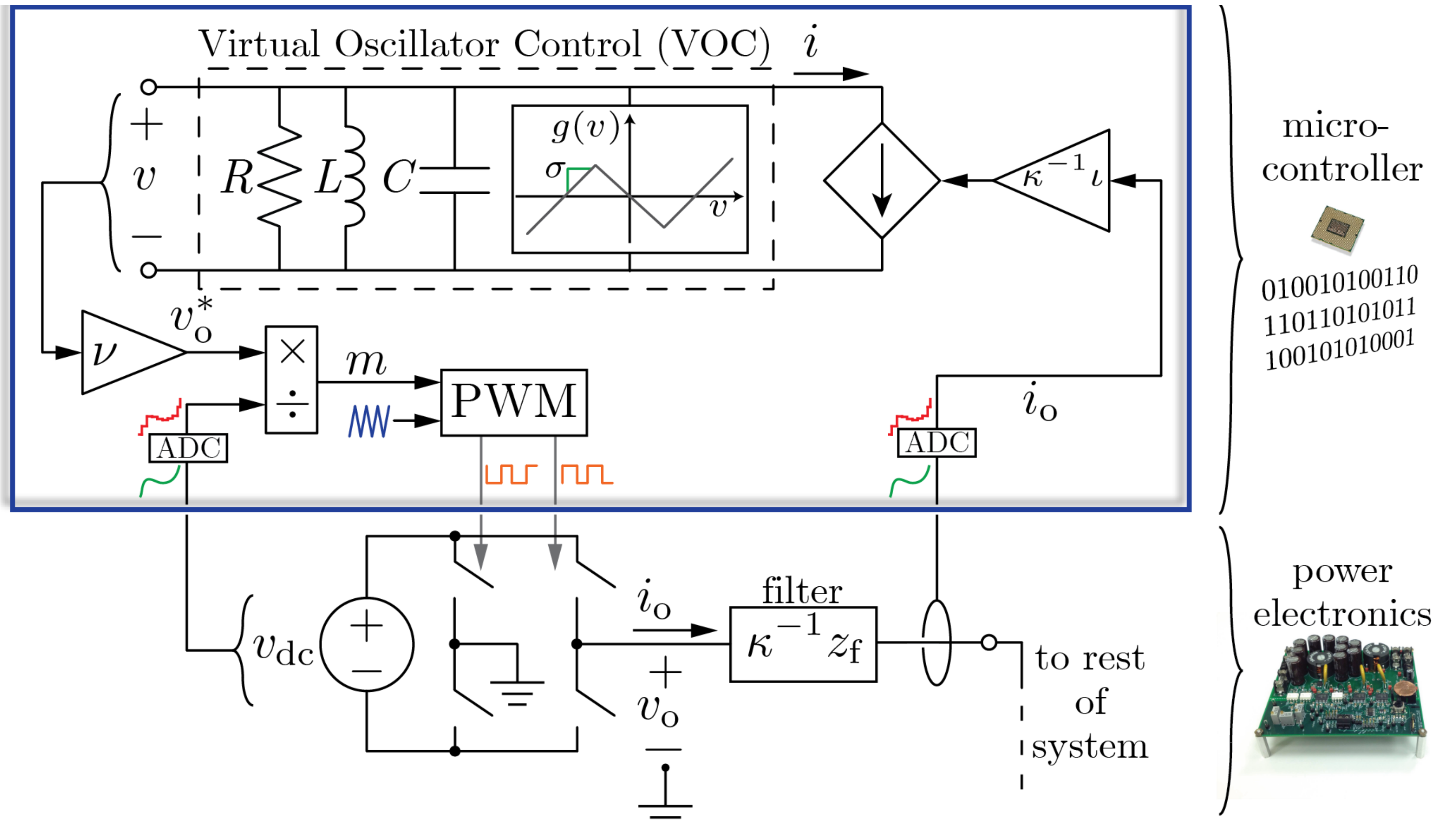
[1] M. Chandorkar, D. Divan, and R. Adapa, “Control of parallel connected inverters in standalone ac supply systems,” *IEEE Transactions on Industrial Applications*, 1993.

[2] R. Lasseter, “Microgrids,” *IEEE PES Winter Meeting*, 2002.

Time-domain Alternative



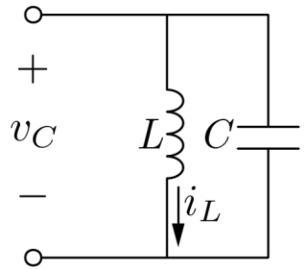
Virtual Oscillator Control: VOC



Features & Advantages

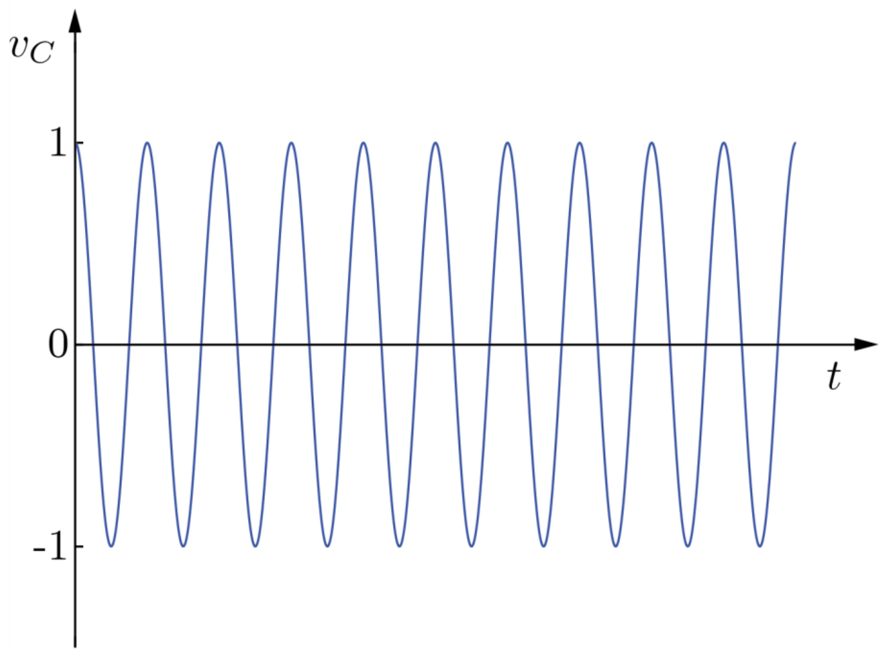
Features & Advantages

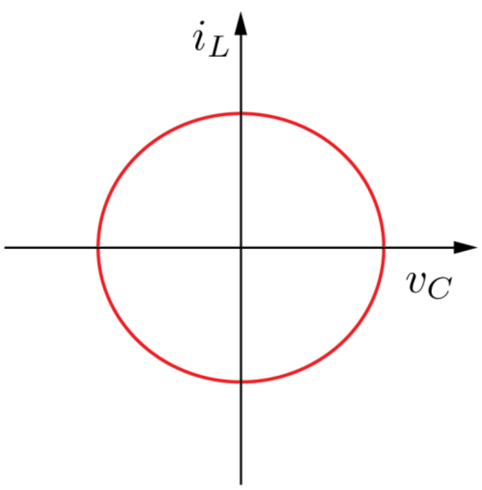
Harmonic Oscillator



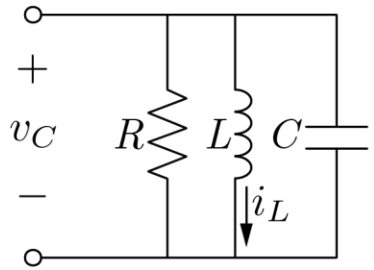
$$\ddot{v}_C + \frac{1}{LC} v_C = 0$$

$$\omega = \frac{1}{\sqrt{LC}}$$



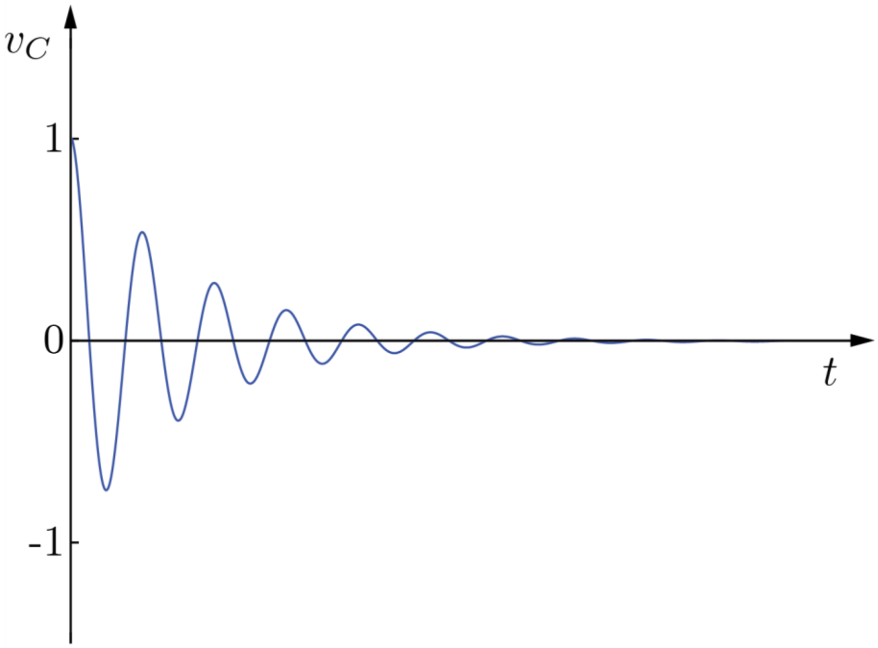


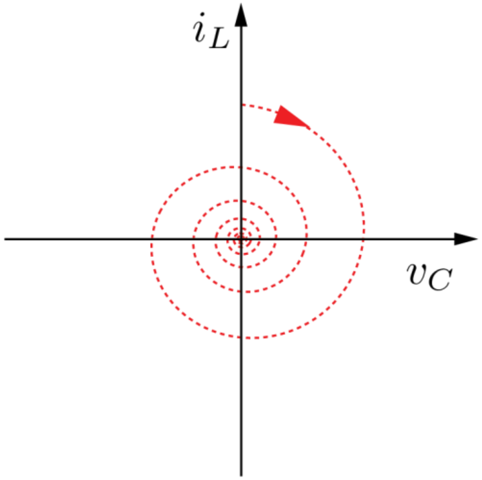
Damped Oscillator



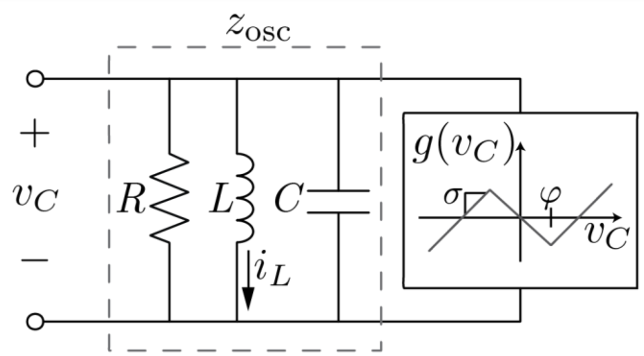
$$\ddot{v}_C + \frac{1}{RC}\dot{v}_C + \frac{1}{LC}v_C = 0$$

$$\omega = \frac{1}{\sqrt{LC}}$$





Dead-zone Oscillator



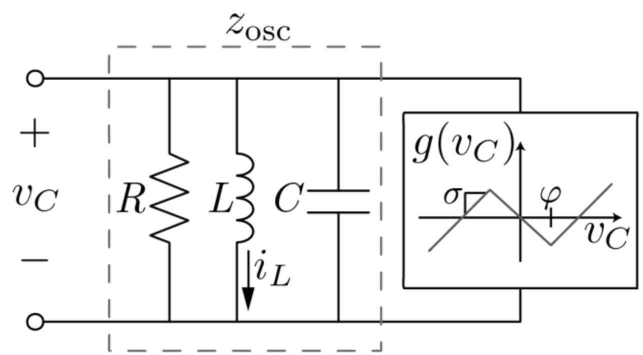
Yields self-sustaining oscillations

Parameter selection:

$\omega = \frac{1}{\sqrt{LC}}$ $\rightarrow$ sets frequency

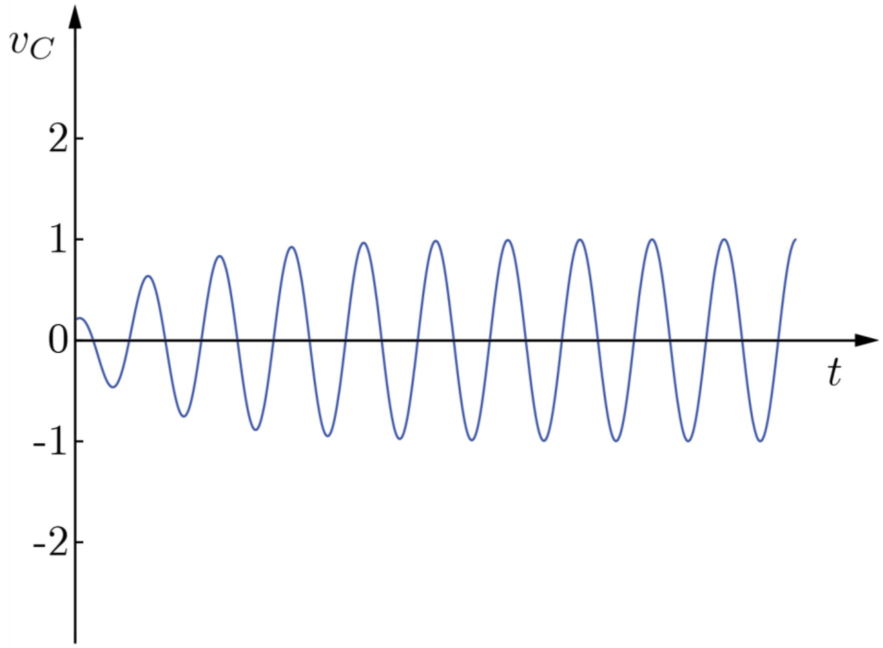
$(\sigma - \frac{1}{R})$ and φ $\rightarrow$ set amplitude

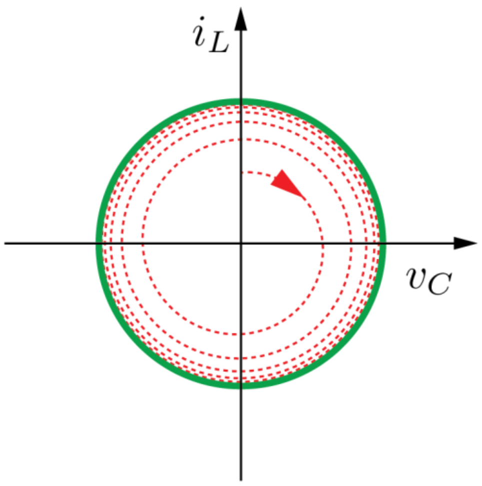
Dead-zone Oscillator



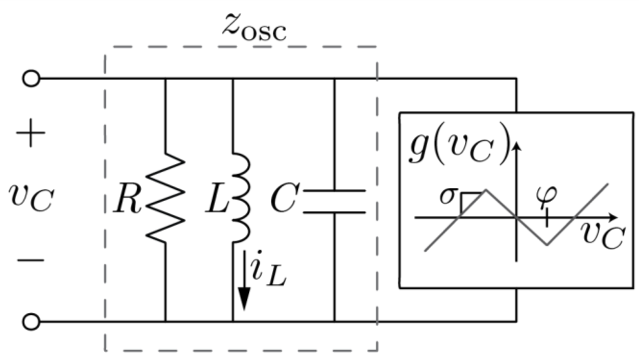
$$\ddot{v}_C + \frac{1}{C}\left(\frac{1}{R} + \frac{dg(v_C)}{dv_C}\right)\dot{v}_C + \frac{1}{LC}v_C = 0$$

$$\omega = \frac{1}{\sqrt{LC}}$$





Dead-zone Oscillator



$$\ddot{v}_C + \frac{1}{C}\left(\frac{1}{R} + \frac{dg(v_C)}{dv_C}\right)\dot{v}_C + \frac{1}{LC}v_C = 0$$

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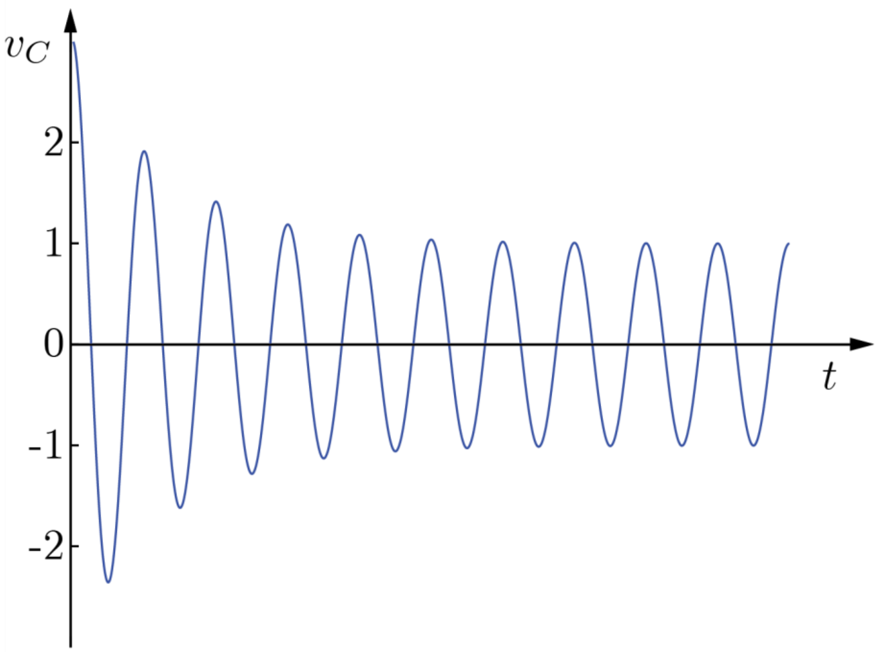
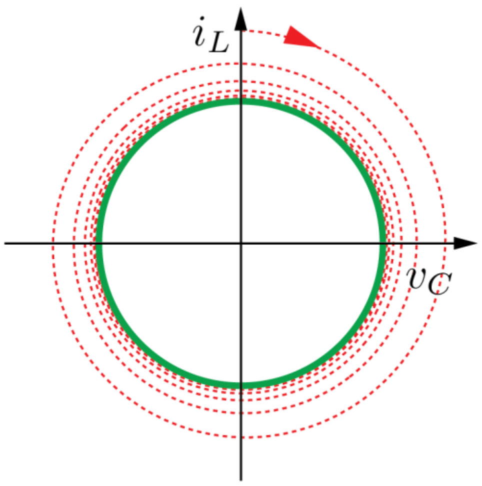
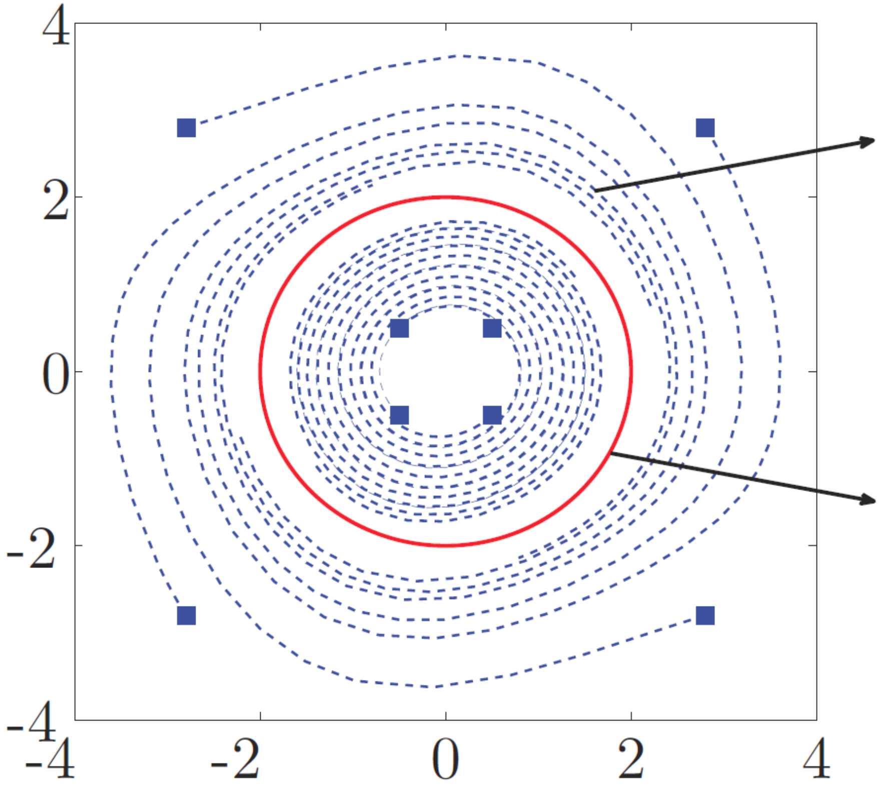




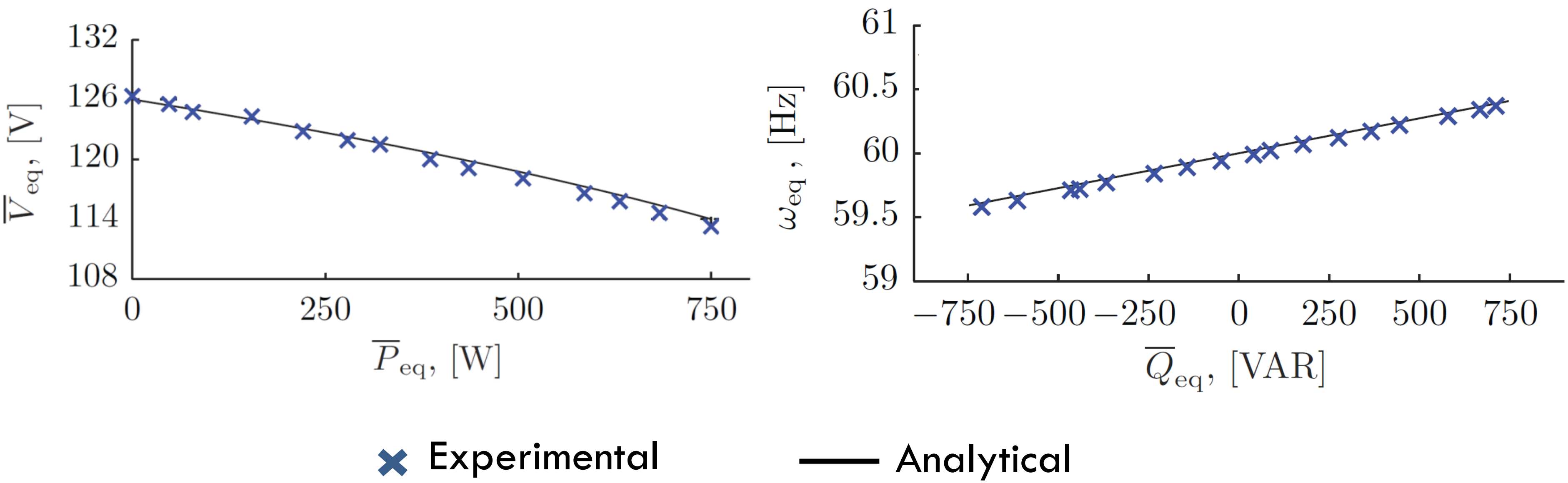
Time-domain Control



VOC stabilizes arbitrary waveforms to sinusoidal steady state

Droop control only acts on sinusoidal steady state

"Contains" Droop

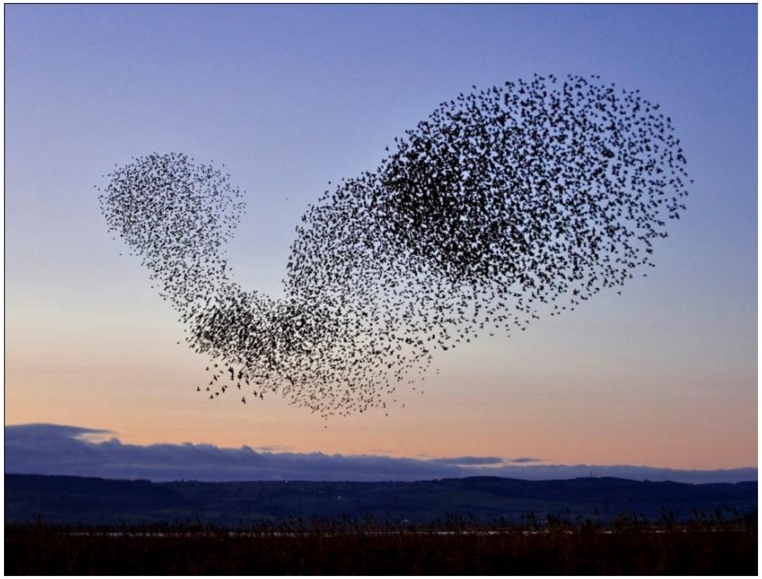


B. Johnson, M. Sinha, N. Ainsworth, F. Dörfler, and S. Dhople, "Synthesizing Virtual Oscillators to Control Islanded Inverters," *IEEE Transactions on Power Electronics*, 2016

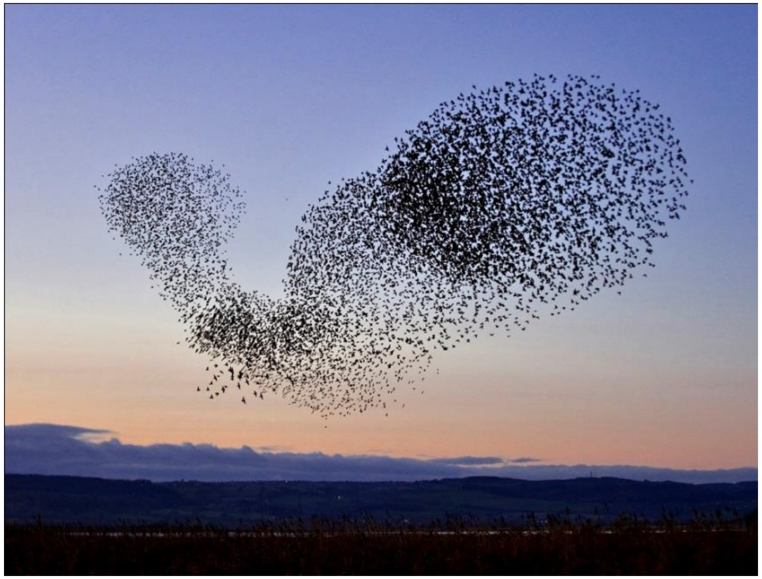
Features & Advantages

Features & Advantages

Synchronization in Nature

Synchronization in Nature



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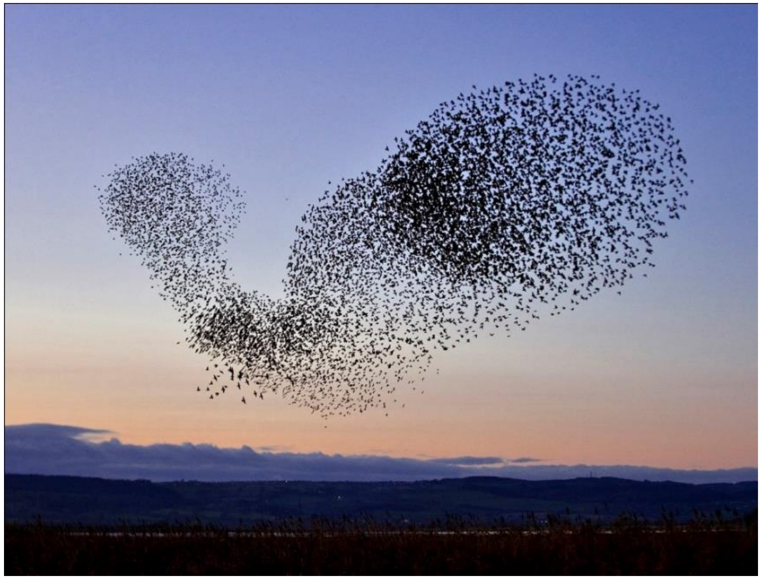
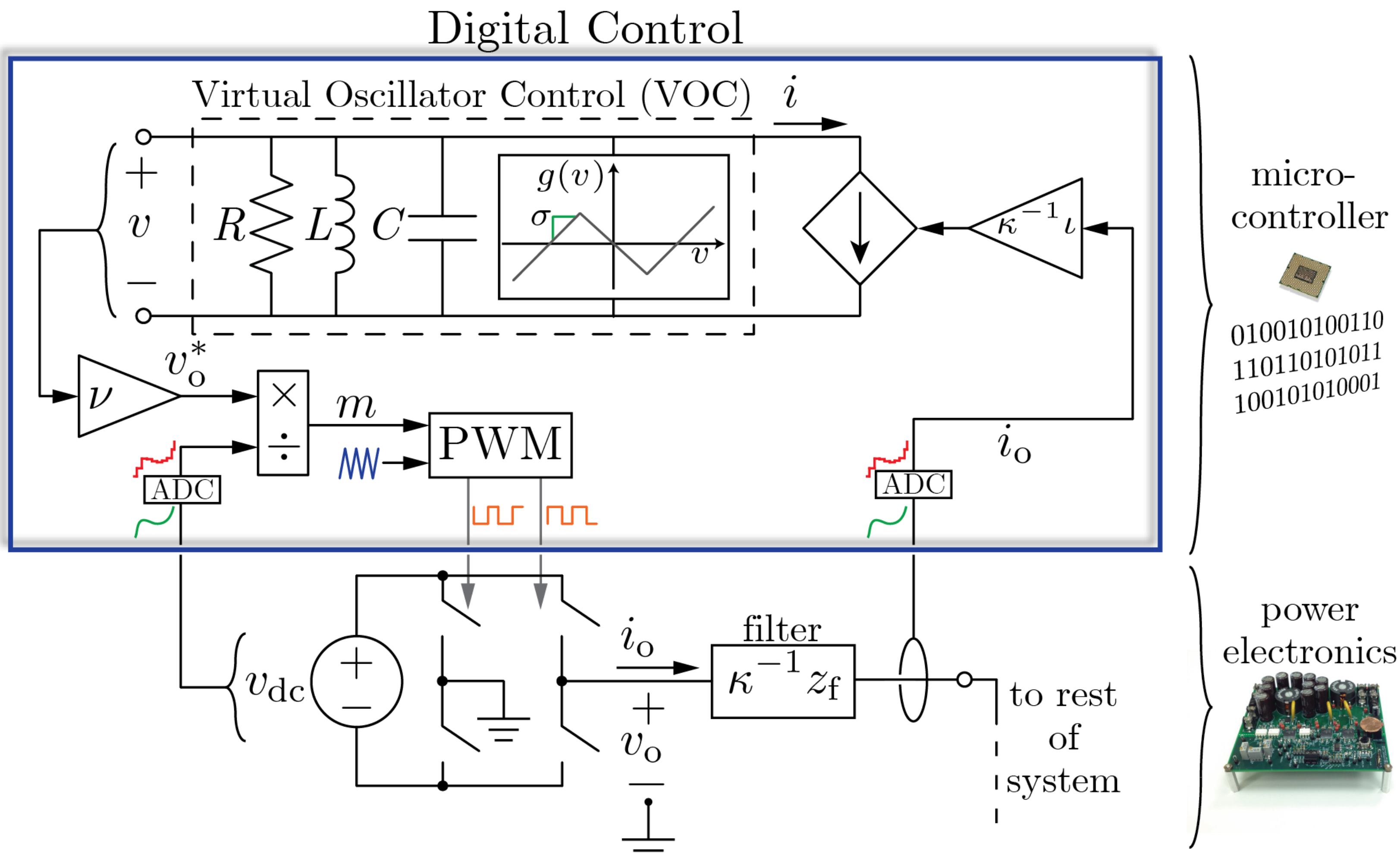
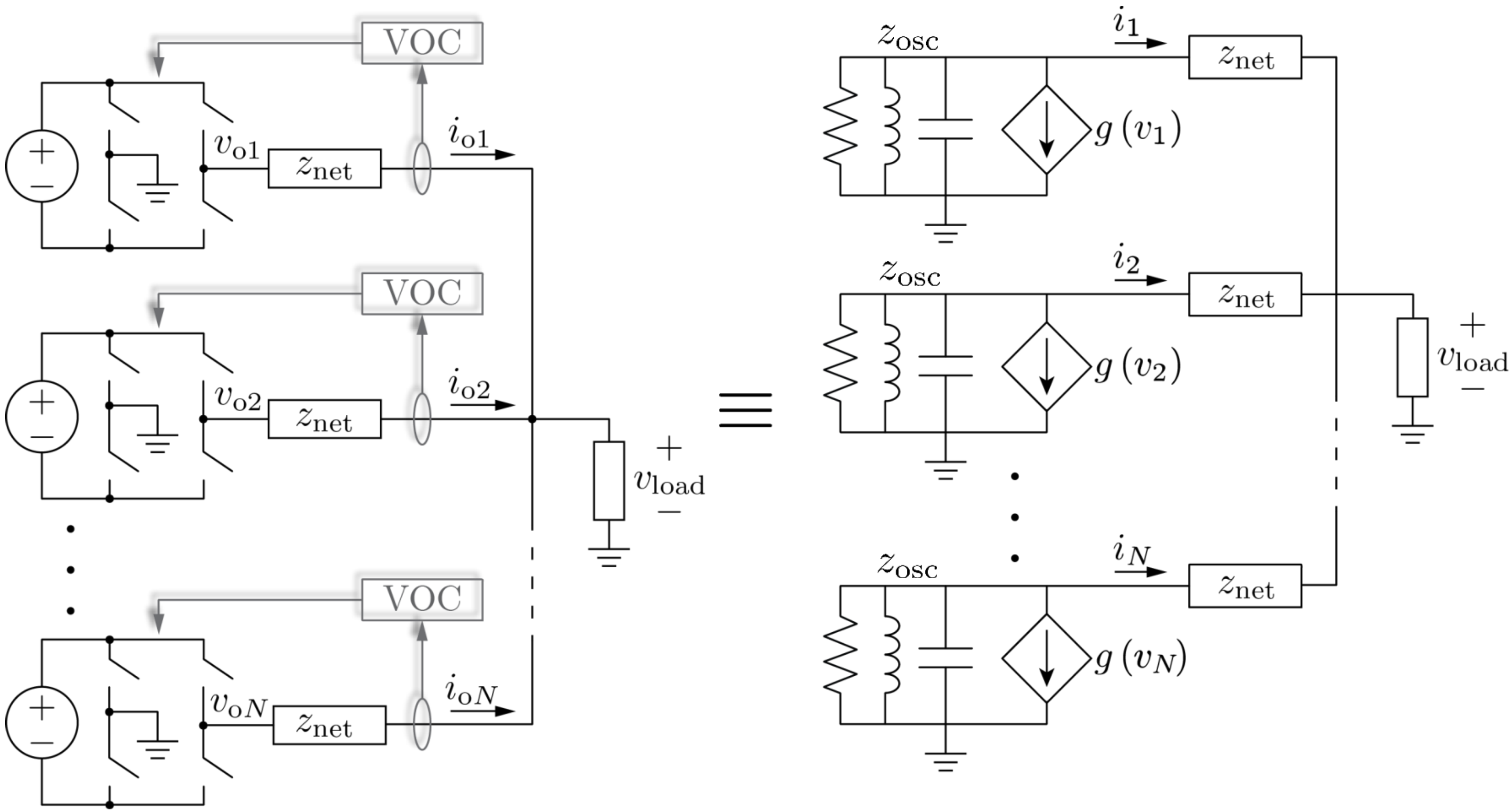


Recall the Controller



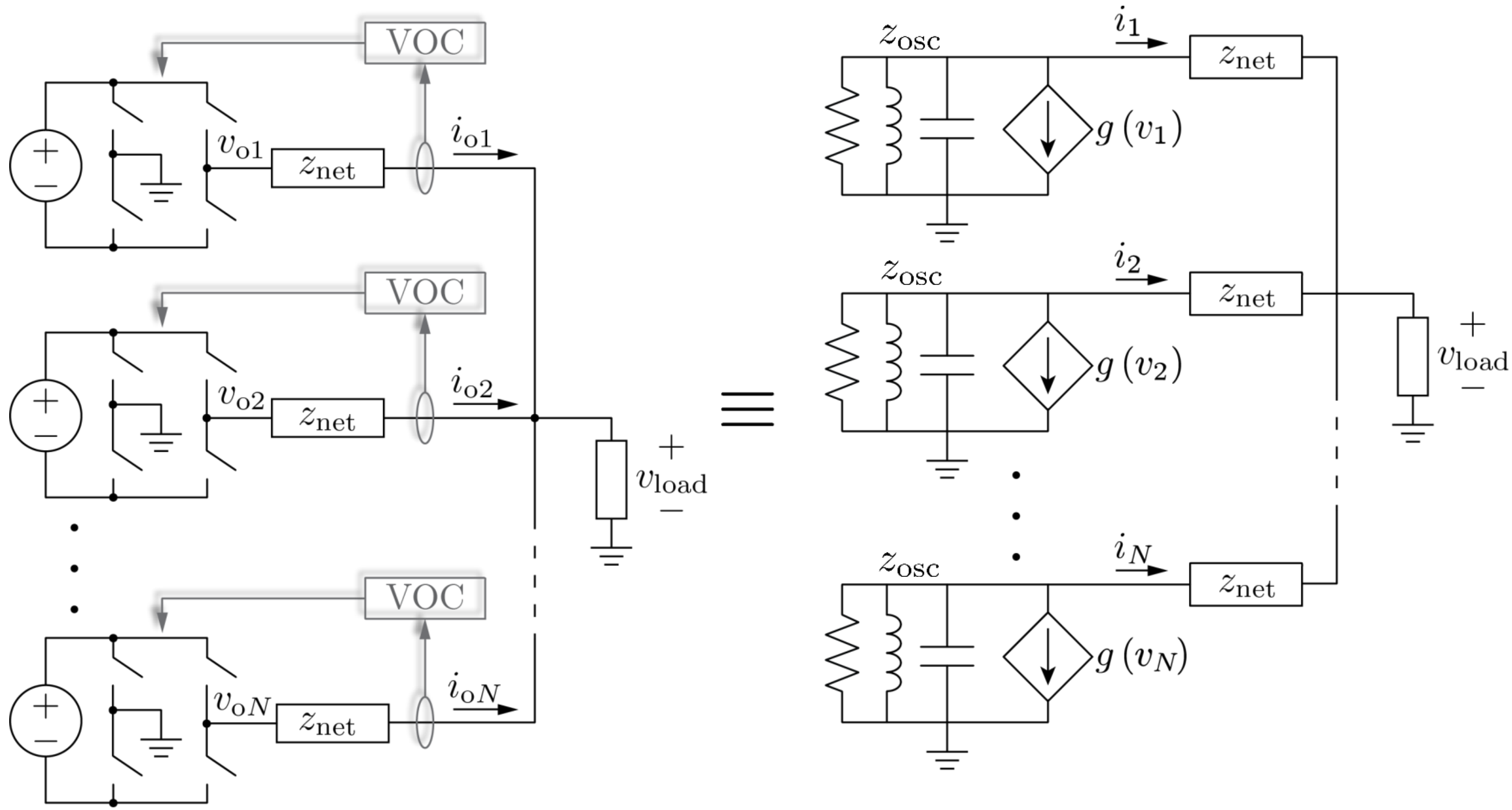
System-level Behavior



Global asymptotic synchronization

$$\lim_{t\to\infty} v_j(t) - v_k(t) = 0 \quad \forall j,k = 1,\ldots,N$$

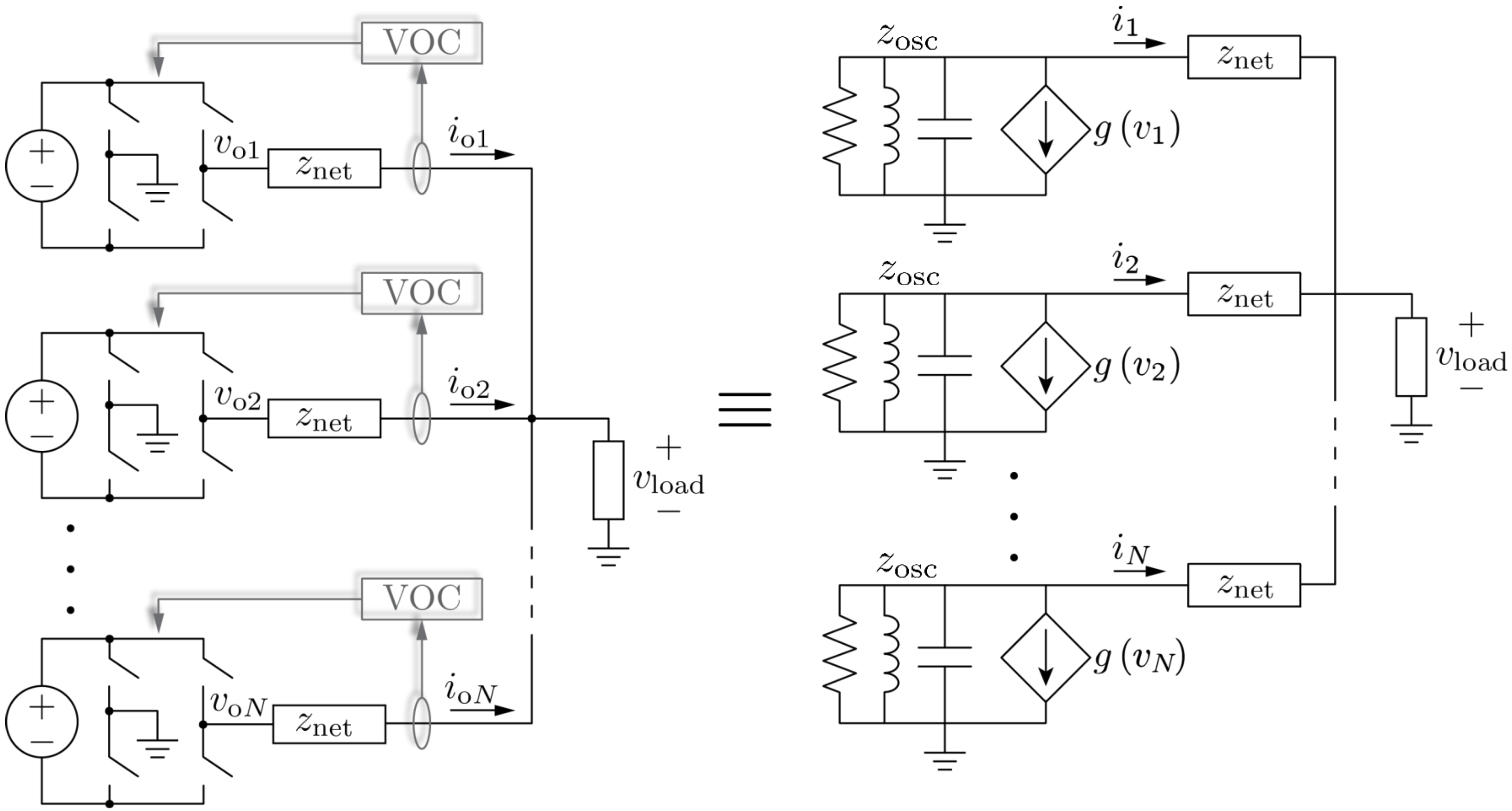
System-level Behavior



Condition for global asymptotic synchronization

$$\sup_{\omega \in \mathbb{R}} \left\| \frac{z_{\mathrm{net}}(j\omega) z_{\mathrm{osc}}(j\omega)}{z_{\mathrm{net}}(j\omega) + z_{\mathrm{osc}}(j\omega)} \right\|_2 \sigma < 1$$

System-level Behavior



- Modular
- Robust
- Resilient

Condition for global asymptotic synchronization

$$\sup_{\omega \in \mathbb{R}} \left\| \frac{z_{net}(j\omega) z_{osc}(j\omega)}{z_{net}(j\omega) + z_{osc}(j\omega)} \right\|_2 \sigma < 1$$

Proof Sketch

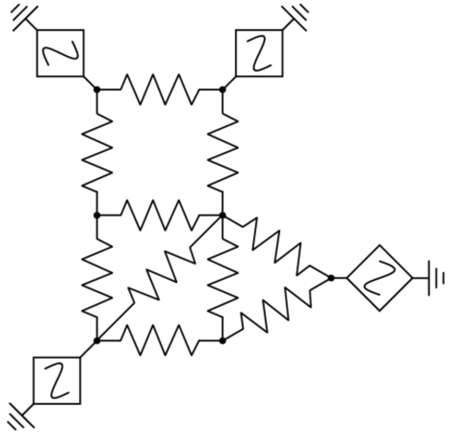
$$\widetilde{\gamma}\left(\mathcal{F}\left(Z_{\mathsf{osc}}(s), Y(s)\right)\right) = \widetilde{\gamma}\left(\mathcal{F}\left(\zeta(s)I, \beta(s)\Gamma\right)\right)$$

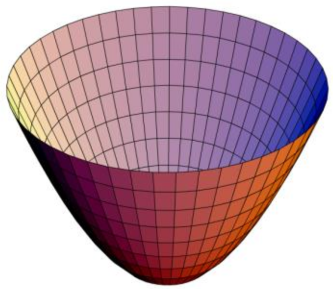
$$= \left\|\mathcal{F}\left(\zeta(s)I, \beta(s)\Gamma\right)\right\|_{\infty}$$

$$= \sup_{\omega \in \mathrm{R}} \frac{\left\| \left(I + \zeta(\mathrm{j}\omega)\beta(\mathrm{j}\omega)\Gamma\right)^{-1} \zeta(\mathrm{j}\omega)\widetilde{i}_{\mathrm{g}}\left(\mathrm{j}\omega\right) \right\|_2}{\|\widetilde{i}_{\mathrm{g}}(\mathrm{j}\omega)\|_2}$$

$$= \sup_{\omega \in \mathrm{R}} \frac{\left\|Q\left(I + \zeta(\mathrm{j}\omega)\beta(\mathrm{j}\omega)\Lambda\right)^{-1} \zeta(\mathrm{j}\omega)Q^{\mathrm{T}}\widetilde{i}_{\mathrm{g}}(\mathrm{j}\omega)\right\|_2}{\|Q^{\mathrm{T}}\widetilde{i}_{\mathrm{g}}(\mathrm{j}\omega)\|_2}$$

State-of-the-Art





- *Existing framework*: Resistive networks
- *Analysis*: Storage function proportional to signal differences[1]-[3]

- *Power systems*: Energy-storage elements pervasive in network
- *Consequences*: Formulation of storage function is difficult

[1] M. Arcak, "Passivity as a design tool for group coordination," *IEEE Transactions on Automatic Control*, 2007.

[2] G.-B. Stan, R. Sepulchre, "Analysis of interconnected oscillators by dissipativity theory," *IEEE Transactions Automatic Control*, 2007.

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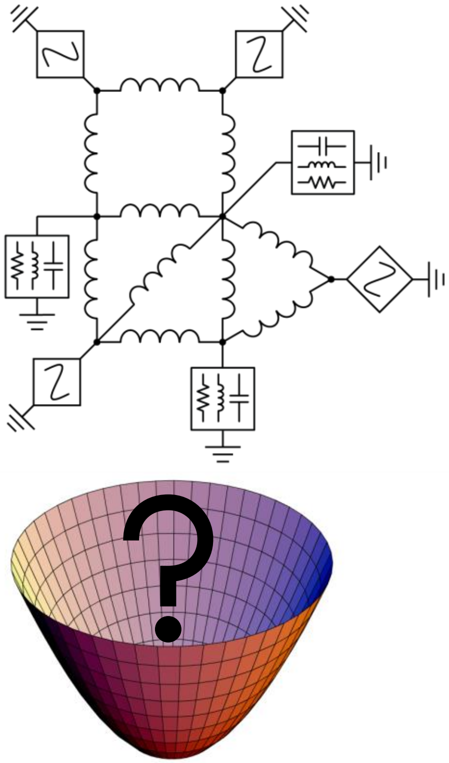

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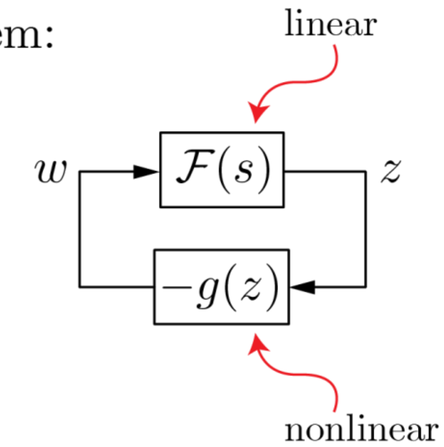
Our Approach

original system:



1) Compartmentalize subsystems

2) Coordinate transformation

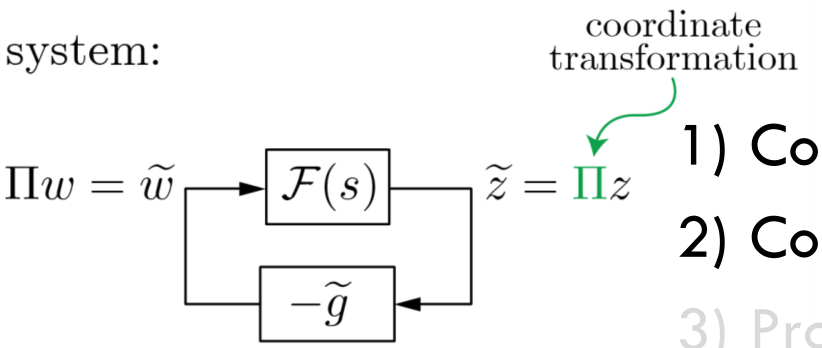
3) Prove stability

[1] S. Dhople, B. Johnson, F. Dörfler, A. Hamadeh, "Synchronization of nonlinear circuits in dynamic electrical networks with general topologies," *IEEE Transactions on Circuits and Systems*, 2014.

[2] B. Johnson, S. Dhople, A. Hamadeh, P. Krein, "Synchronization of nonlinear oscillators in an LTI electrical network," *IEEE Transactions on Circuits and Systems*, 2014.

Our Approach

differential system:



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Our Approach

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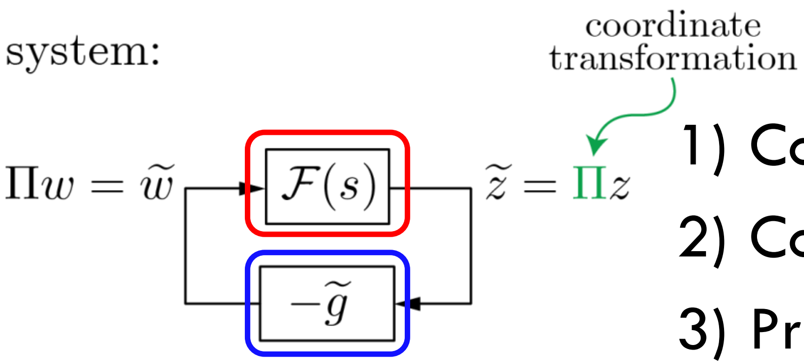

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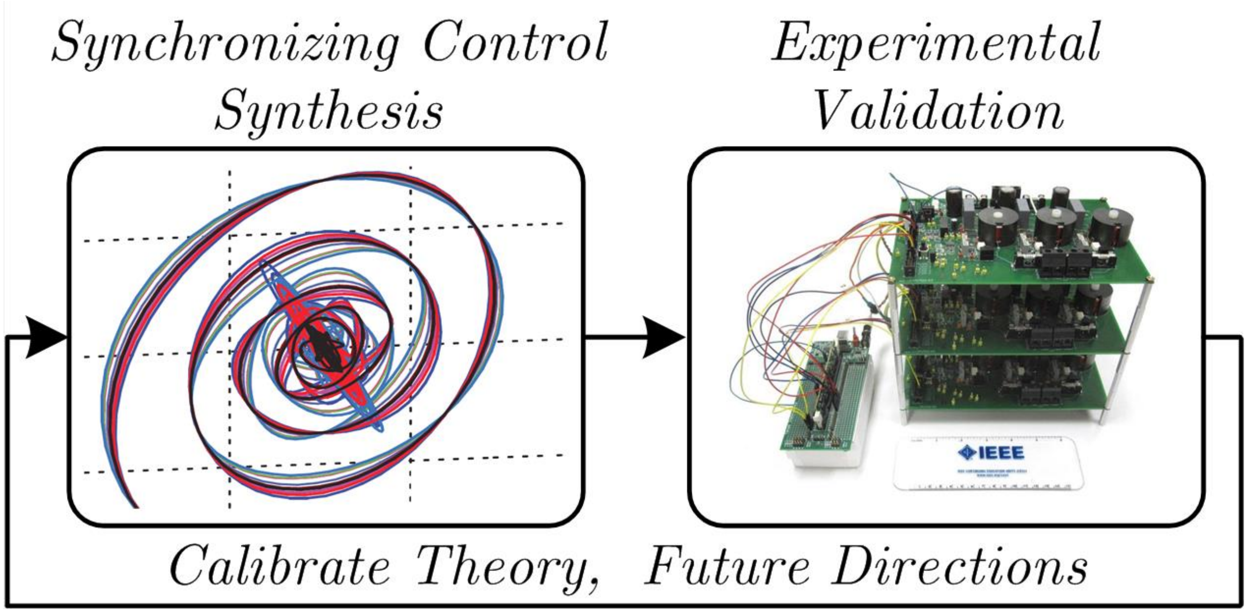
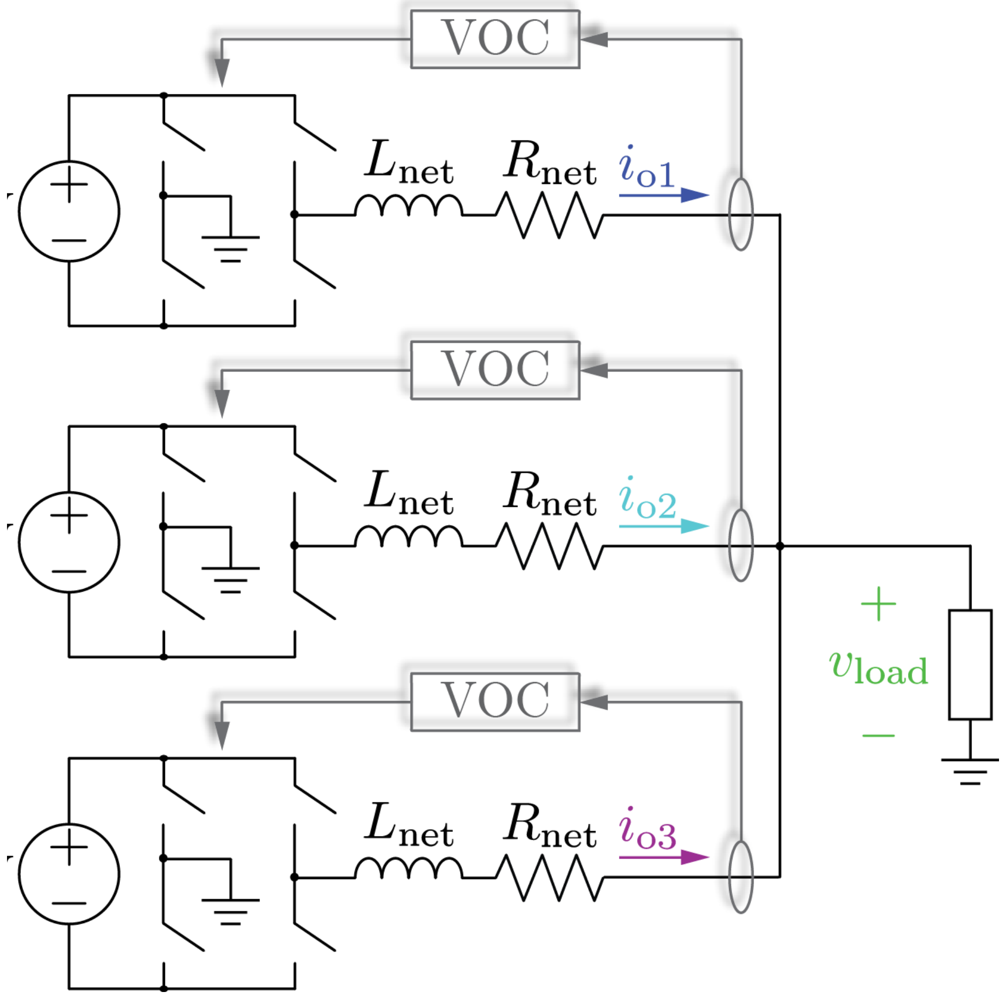
Research Philosophy

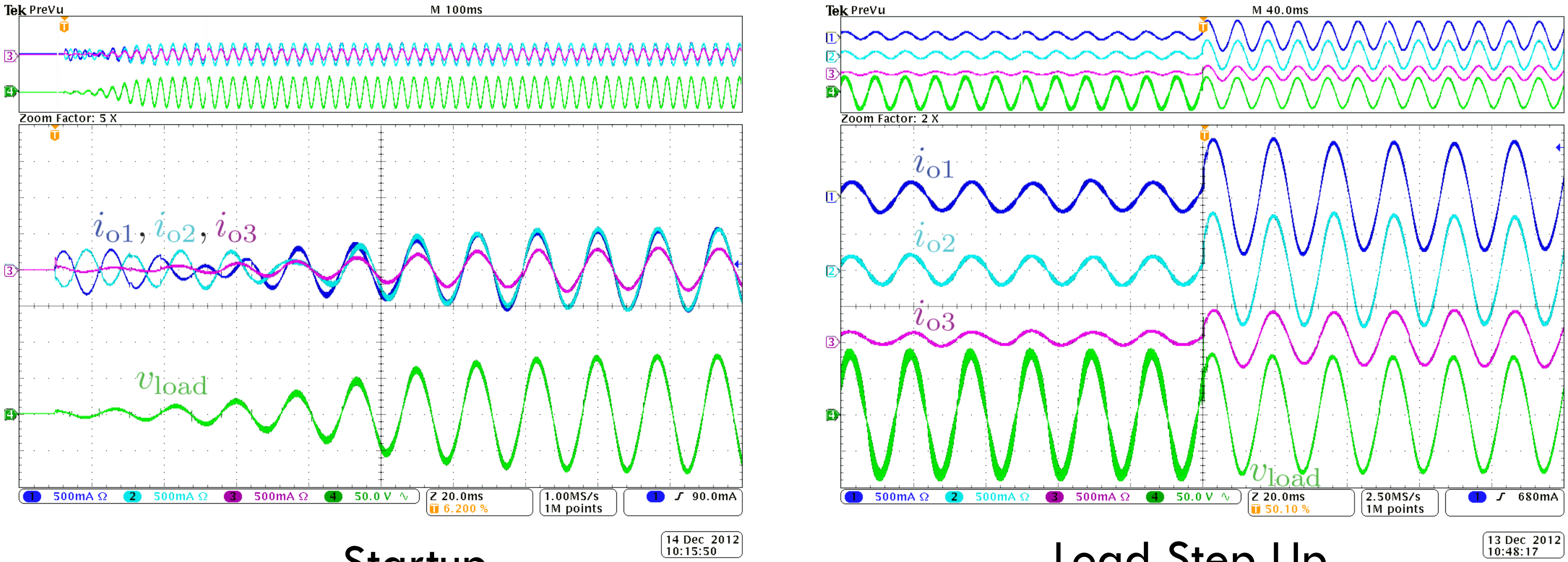


Experimental Setup



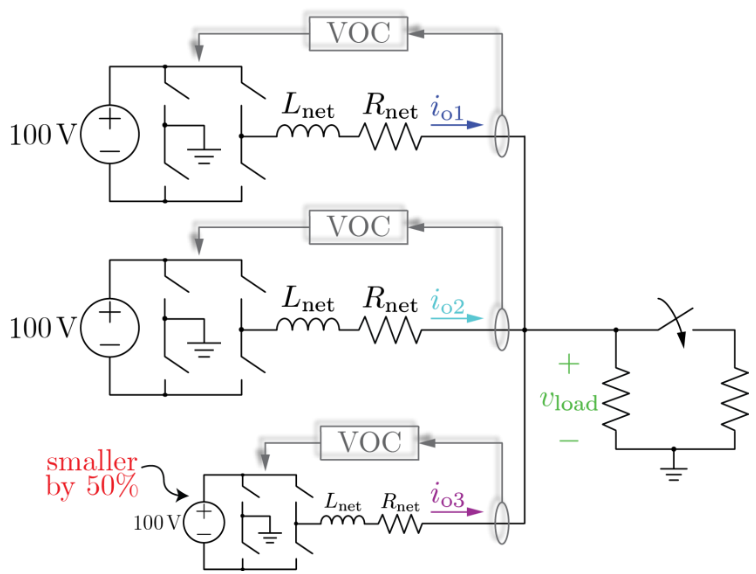
[1] B. Johnson, S. Dhople, A. Hamadeh, and P. Krein, “Synchronization of parallel single-phase inverters with virtual oscillator control,” *IEEE Transactions on Power Electronics*, 2014.

Resistive Load (Sharing)

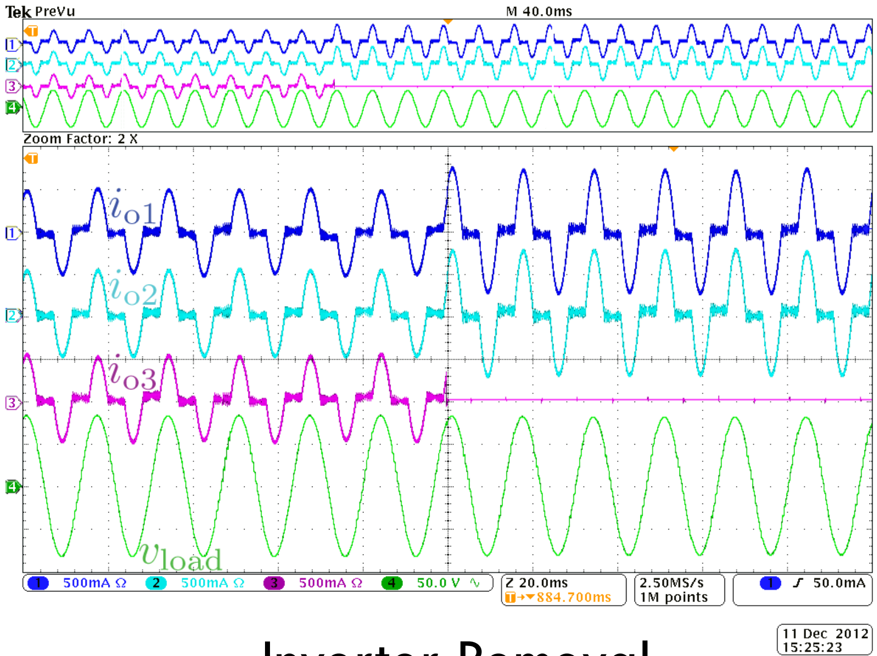


Startup

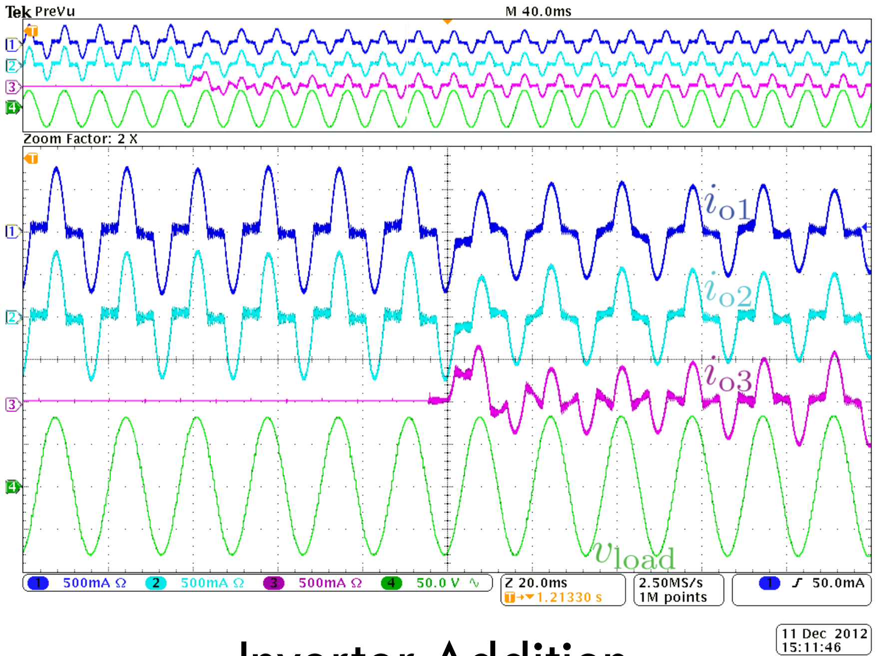
Load Step Up



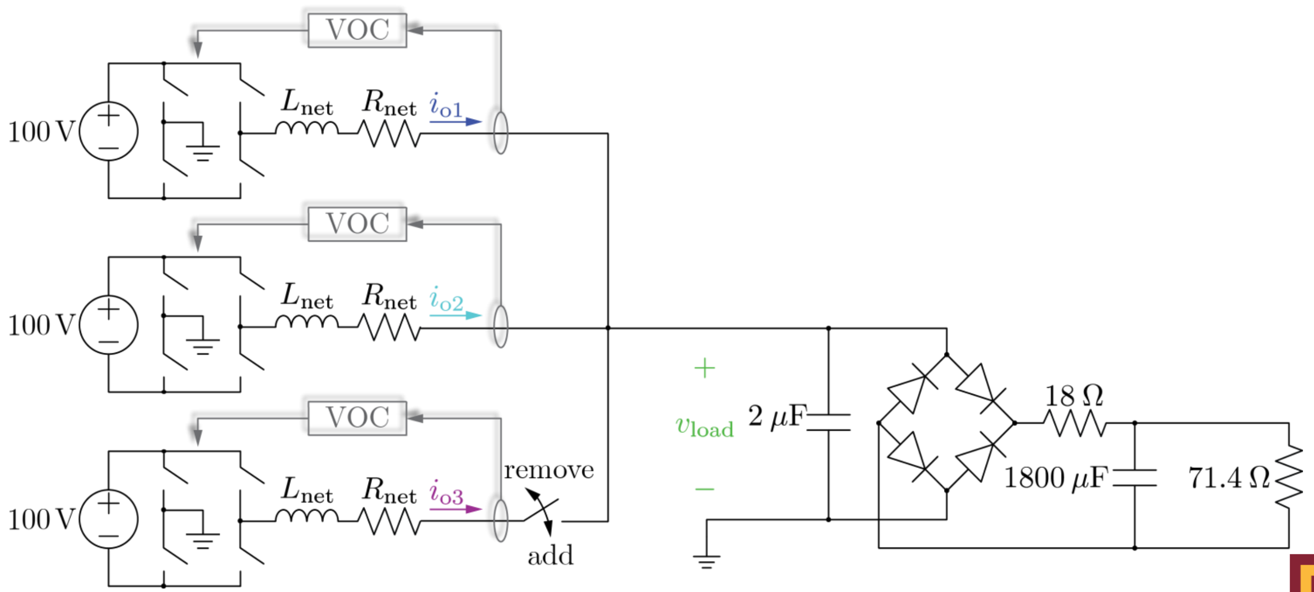
Nonlinear Load



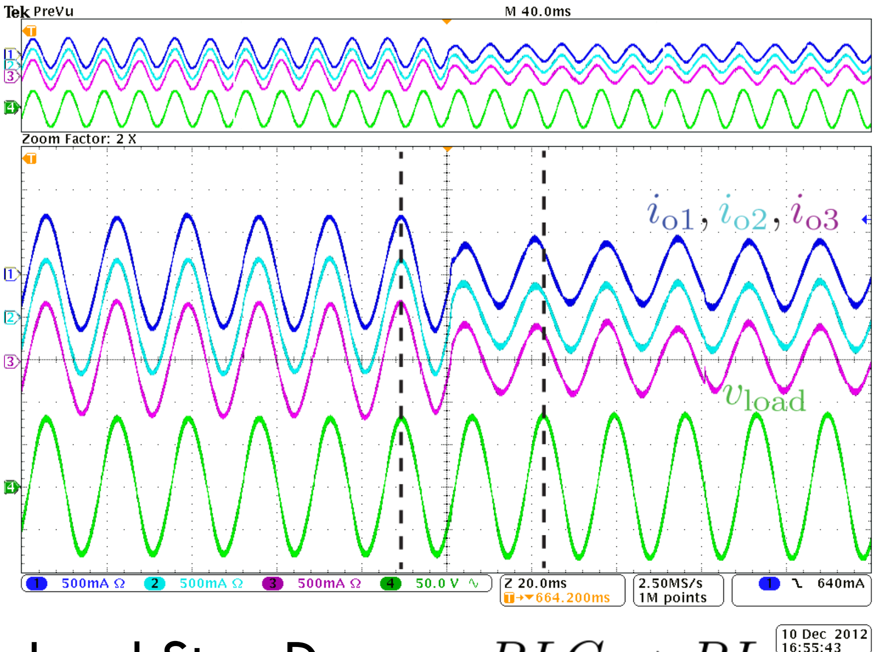
Inverter Removal



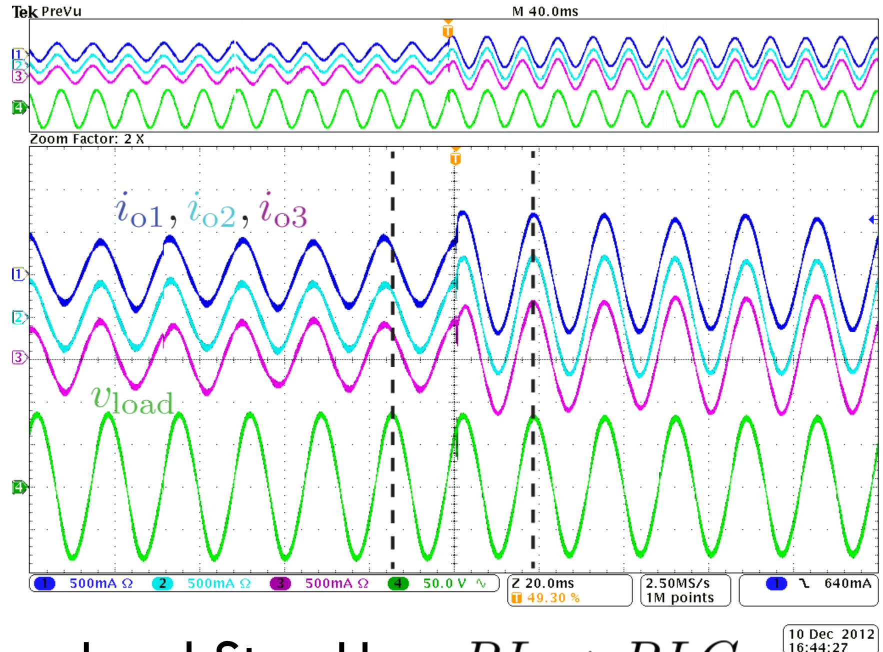
Inverter Addition



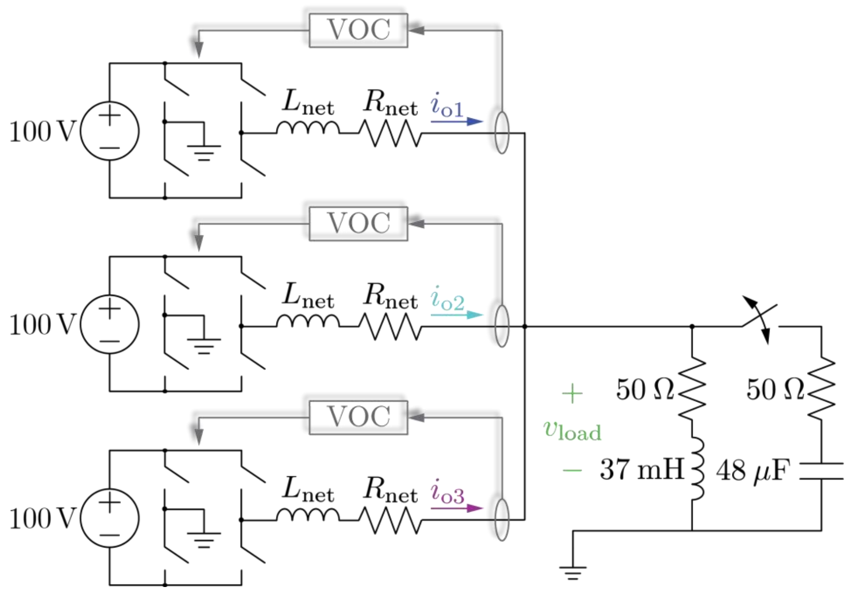
RLC Load



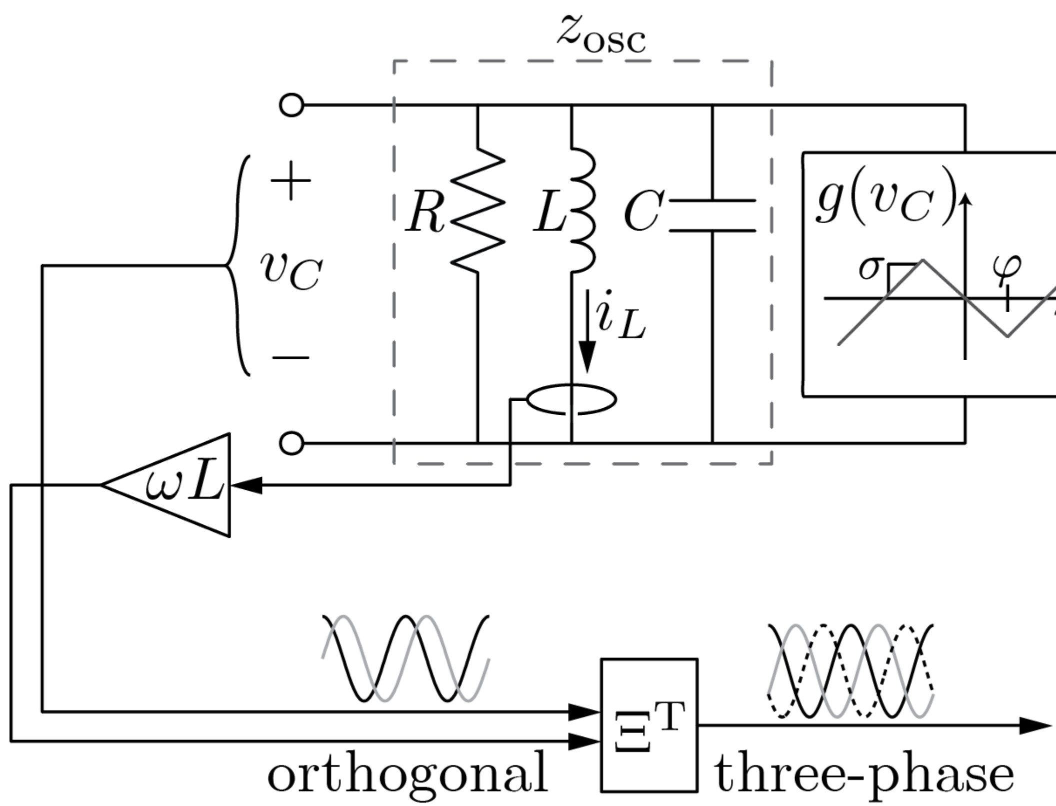
Load Step Down: $RLC \to RL$



Load Step Up: $RL \to RLC$



Three-phase Systems



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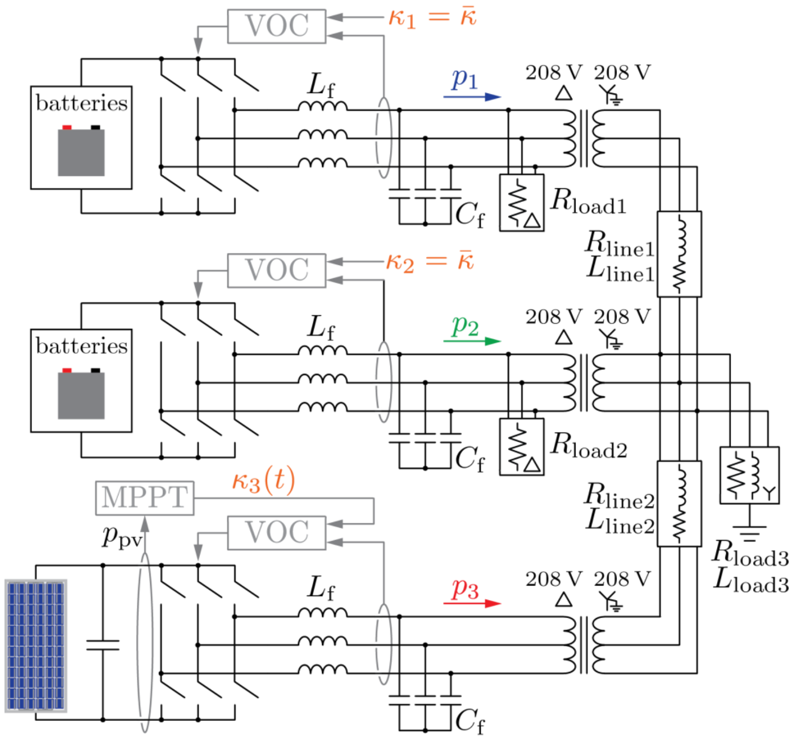
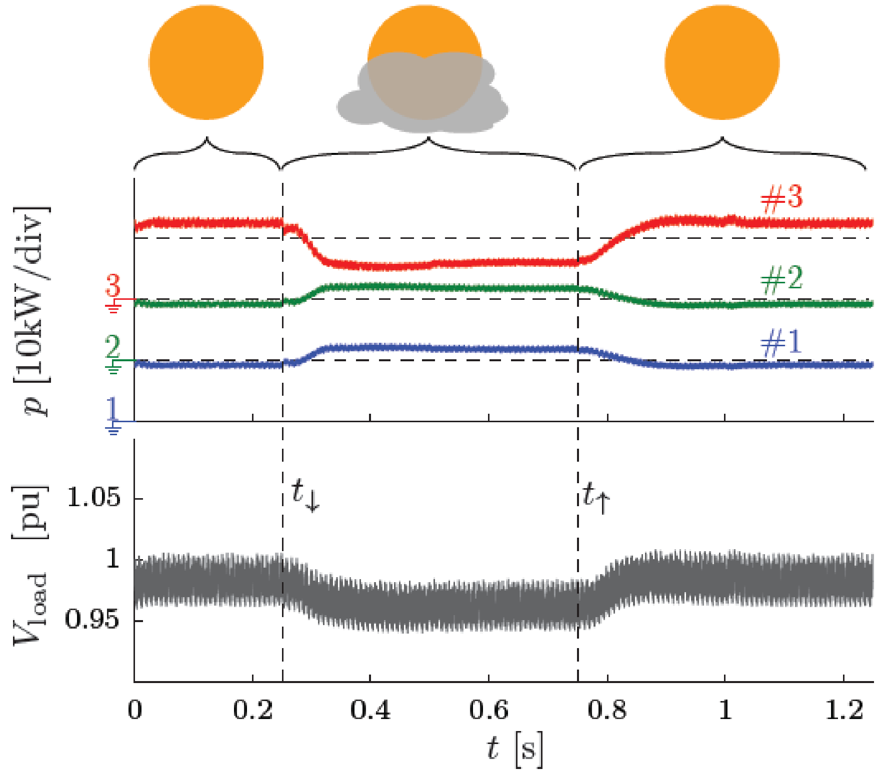
Three-phase Systems





- Three-phase systems with PV
- MPPT functionality incorporated
- Load satisfied despite variable PV generation

[1] B. Johnson, S. Dhople, J. Cale, A. Hamadeh, P. Krein, "Oscillator-based control for islanded three-phase microgrids," *IEEE Journal of Photovoltaics*, 2014.

Summary

- Time-domain control alternative to droop control
- Theoretical guarantees at inverter- and system-level
- Translational impacts: circuit theory, physics, systems biology
- Future work: interoperability, dispatchability, coordination

?

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