Nonlinear Decentralized Control for Future Grids

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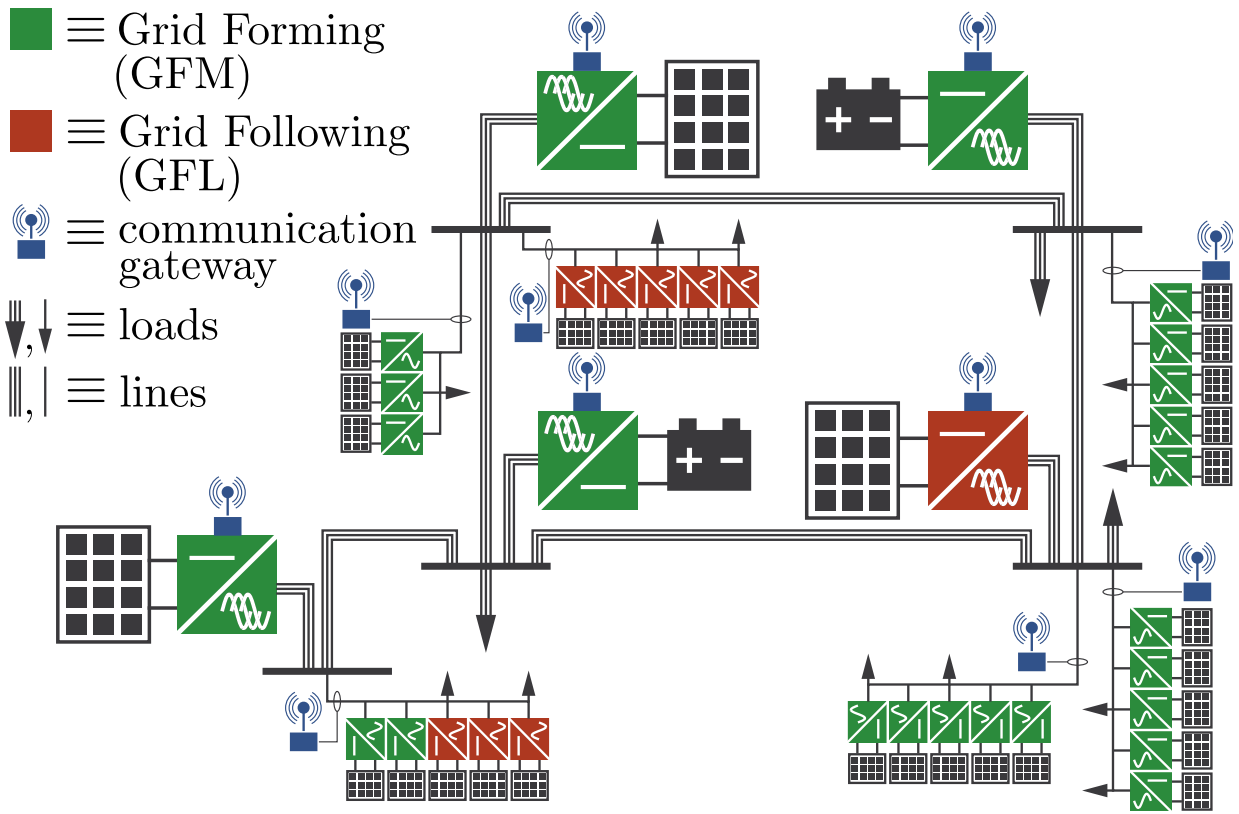
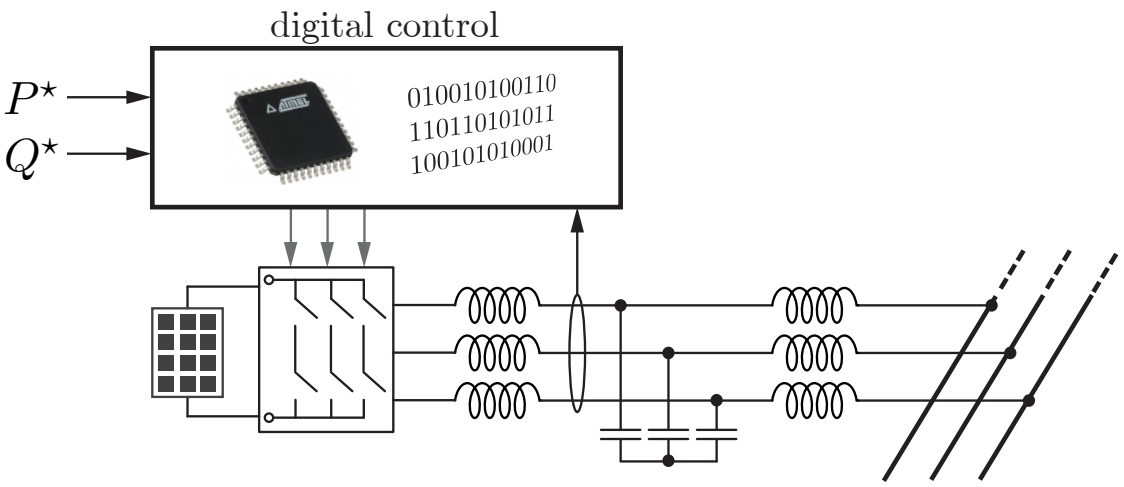
ELECTRICAL & COMPUTER ENGINEERING

UNIVERSITY *of* WASHINGTON

The Future Grid



The Ideal Power Electronics Interface



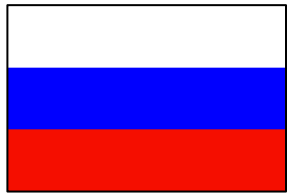
Wishlist

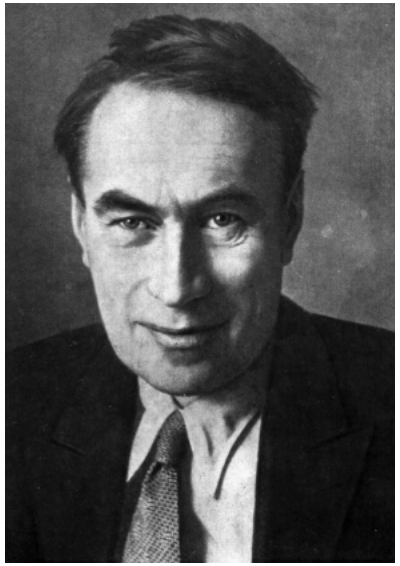
- Works across high to zero inertia
- Compatible in both grid-connected & islanded
- Robustly synchronizes in large networks
- Rapid convergence to steady state
- Can act on exogenous setpoints
- Produces high quality voltage waveform
- Controller has unambiguous design procedure
- Integrated droop functions

Seeking Inspiration from Historical Figures

Balthasar van der Pol

1889-1959





Aleksandr Andronov

1901-1952

Seeking Inspiration from Historical Figures & their Models

$$\dot{x}_1 = \varepsilon\omega_0(\sigma x_1 - \alpha x_1^3) - \omega_0 x_2,$$
$$\dot{x}_2 = \omega_0 x_1.$$

Balthasar van der Pol

1889-1959

$$\dot{x}_1 = \varepsilon\omega_0(\sigma x_1 - \alpha\|x\|^2 x_1) - \omega_0 x_2,$$
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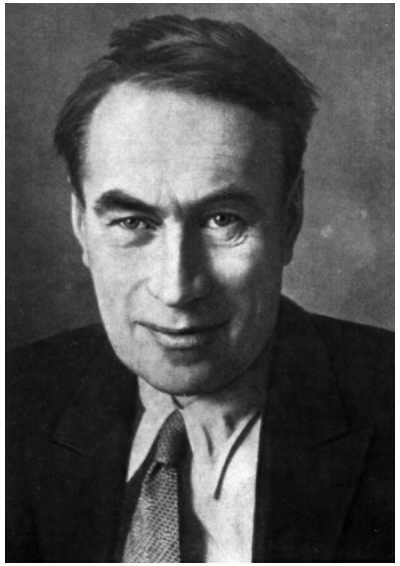


Aleksandr Andronov

1901-1952

Circuit Interpretations of Nonlinear Oscillators

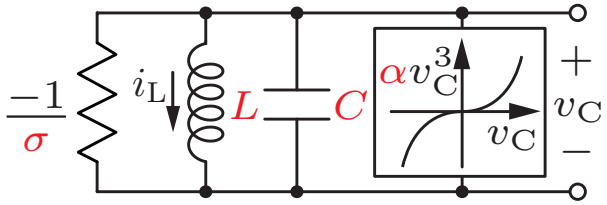
$$\dot{x}_1 = \varepsilon\omega_0(\sigma x_1 - \alpha x_1^3) - \omega_0 x_2,$$
$$\dot{x}_2 = \omega_0 x_1.$$

$$\downarrow$$

$$C\frac{\mathrm{d}v_\mathrm{C}}{\mathrm{d}t} = -i_\mathrm{L} - \alpha v_\mathrm{C}^3 + \sigma v_\mathrm{C},$$
$$L\frac{\mathrm{d}i_\mathrm{L}}{\mathrm{d}t} = v_\mathrm{C},$$

where $\varepsilon := \sqrt{\frac{L}{C}}$.

$$\Downarrow$$



Circuit for van der Pol

$$\dot{x}_1 = \varepsilon\omega_0(\sigma x_1 - \alpha\|x\|^2 x_1) - \omega_0 x_2,$$
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$$C\frac{\mathrm{d}v_\mathrm{C}}{\mathrm{d}t} = -i_\mathrm{L} - \alpha(v_\mathrm{C}^2 + \varepsilon^2 i_\mathrm{L}^2)v_\mathrm{C} + \sigma v_\mathrm{C},$$
$$L\frac{\mathrm{d}i_\mathrm{L}}{\mathrm{d}t} = v_\mathrm{C},$$

where $\varepsilon := \sqrt{\frac{L}{C}}$.

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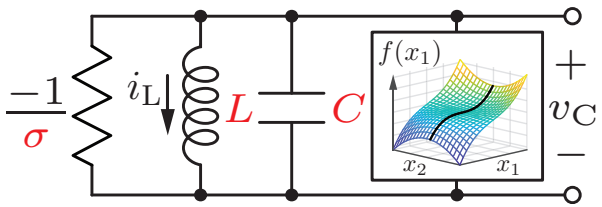
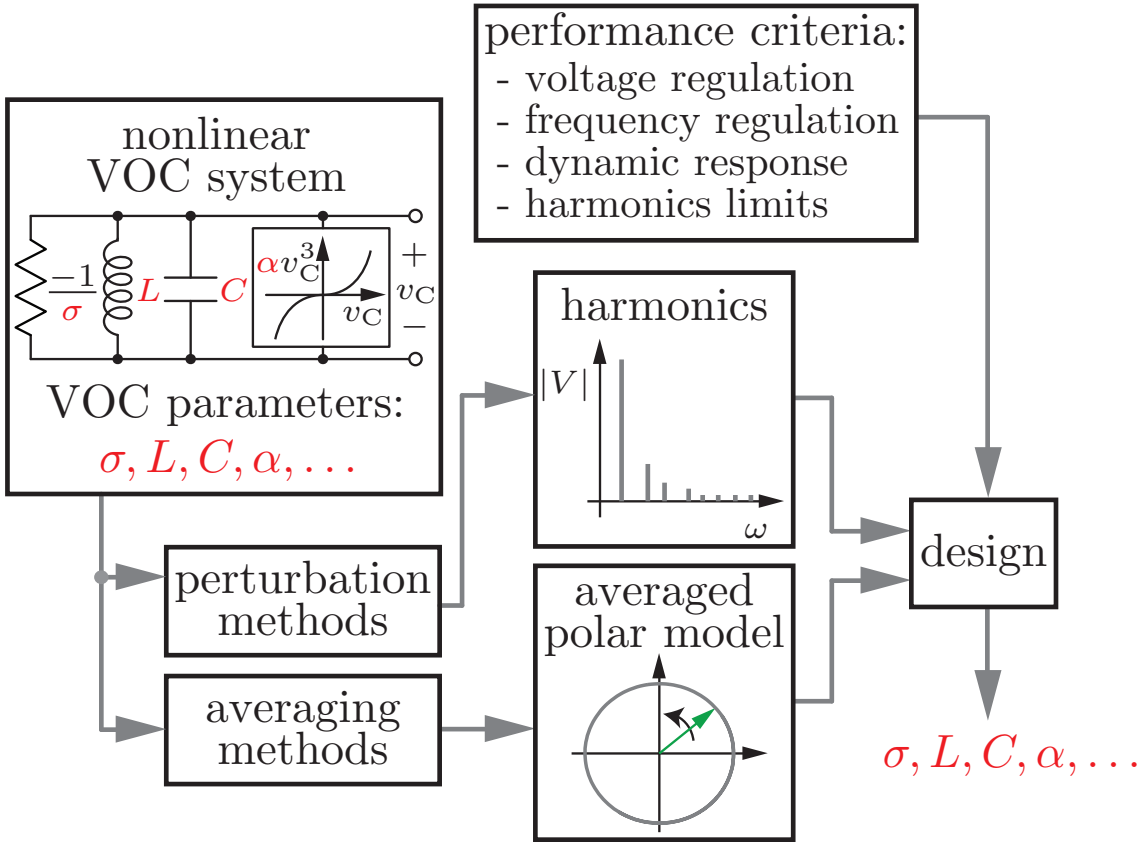


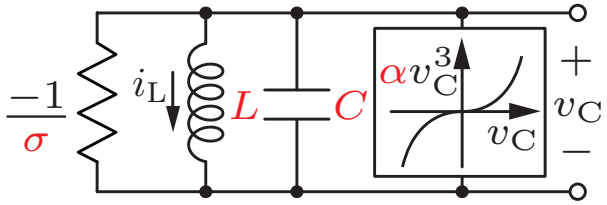
Circuit for Andronov

Oscillator Design

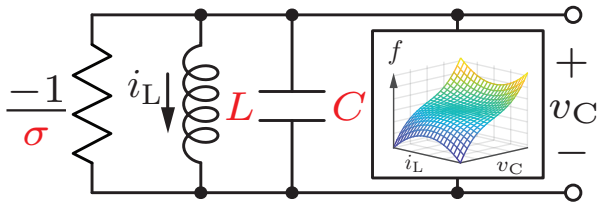


Key Parametric Relations

$\omega = \left(1 - \frac{\varepsilon^2\sigma^2}{16}\right)\omega_0$	frequency	$\omega = \omega_0$
$t_{\text{rise}} = \frac{6}{\varepsilon\sigma\omega_0}$	speed	$t_{\text{rise}} = \frac{6}{\varepsilon\sigma\omega_0}$
$\frac{\text{third}}{\text{fundamental}} = \frac{\varepsilon\sigma}{8}$	harmonics	$\frac{\text{third}}{\text{fundamental}} = 0$



Circuit for van der Pol



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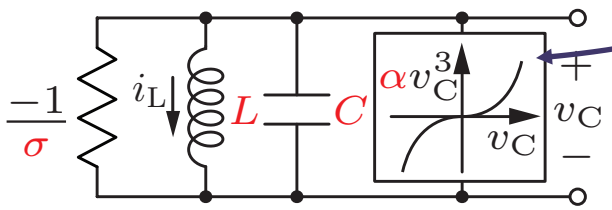
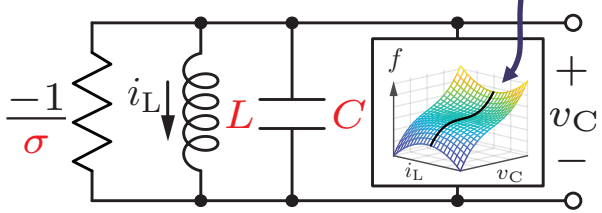
Andronov

$\supset$

van der Pol



Circuit for van der Pol



Circuit for Andronov

Key Parametric Relations

tradeoffs

$\omega = \left(1 - \frac{\varepsilon^2\sigma^2}{16}\right)\omega_0$	frequency	$\omega = \omega_0$
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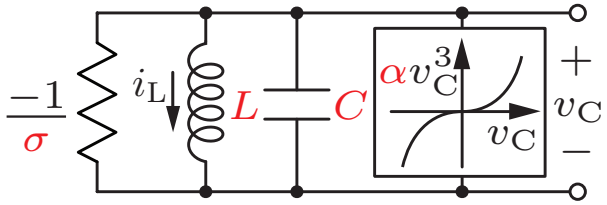
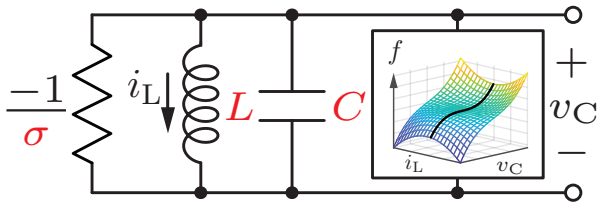


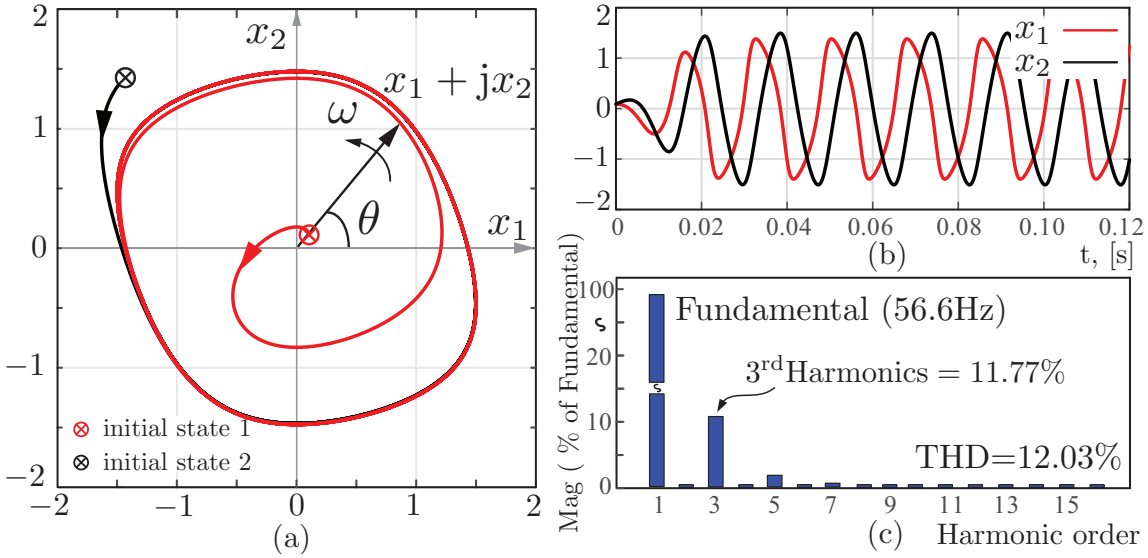
Circuit for van der Pol



Circuit for Andronov

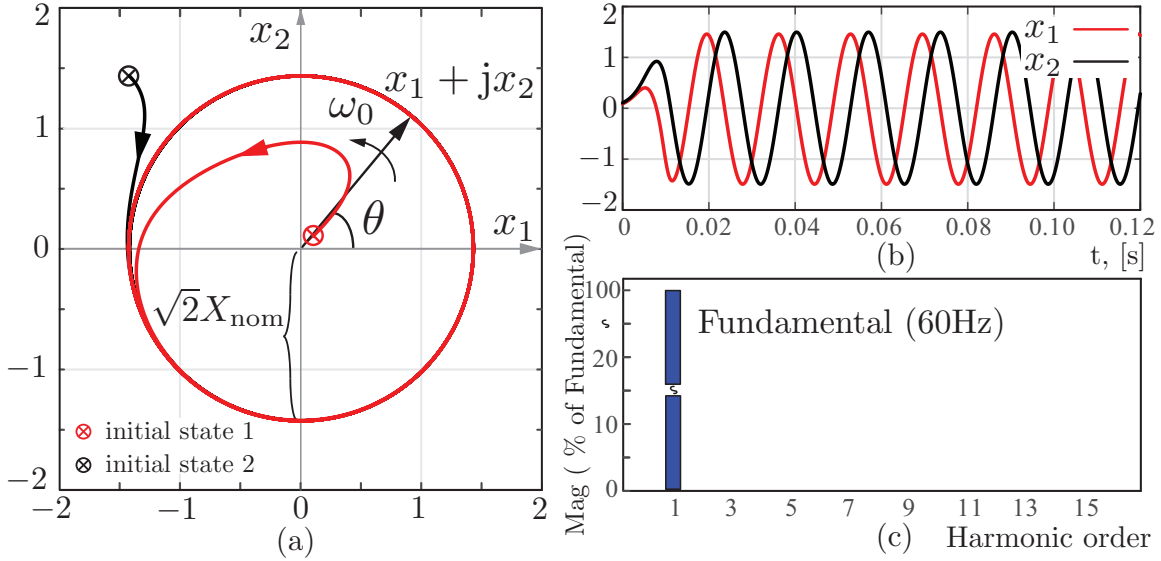
Dynamic Performance Comparison

Parameters chosen for $\varepsilon\sigma = 1$

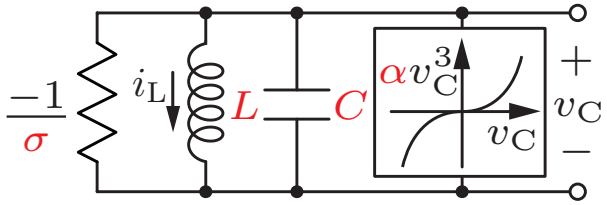


off-nominal frequency, low quality waveform, fast

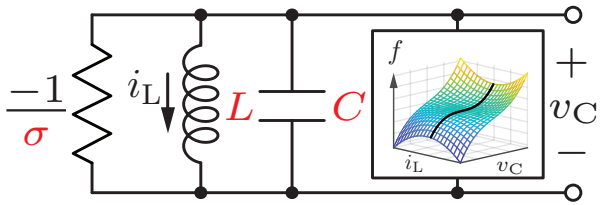
Parameters chosen for $\varepsilon\sigma = 1$



nominal frequency, high quality waveform, fast



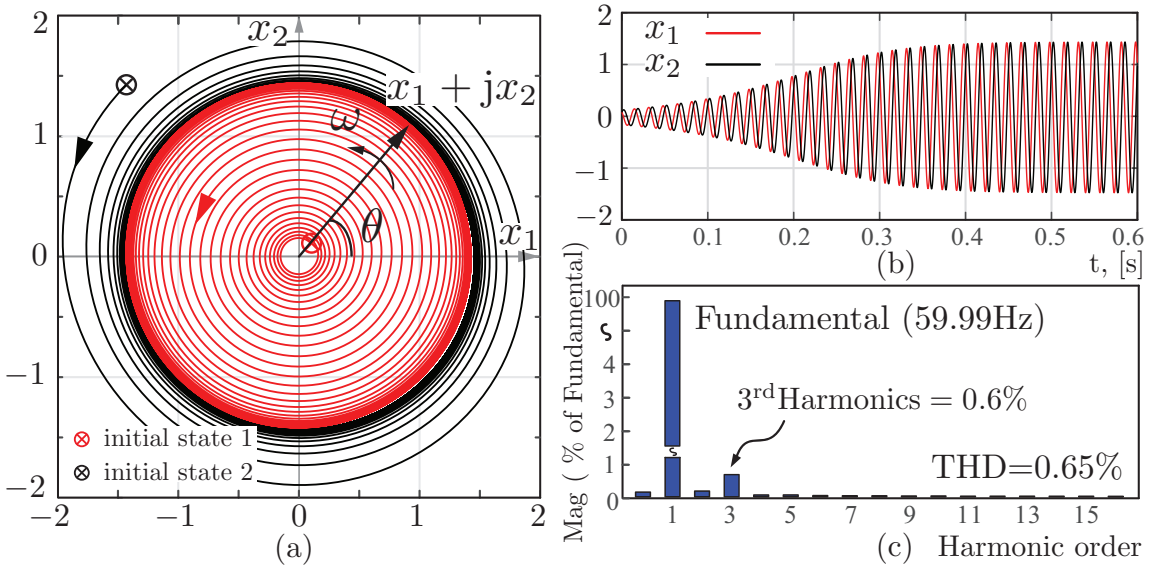
Circuit for van der Pol



Circuit for Andronov

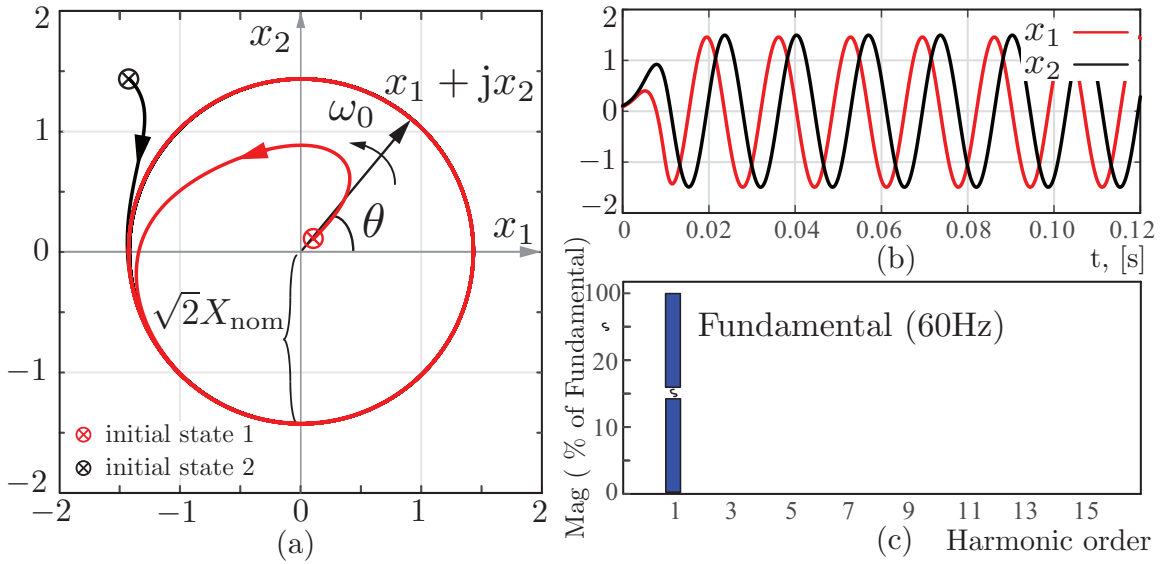
Dynamic Performance Comparison

Parameters chosen for $\varepsilon\sigma = 0.05$

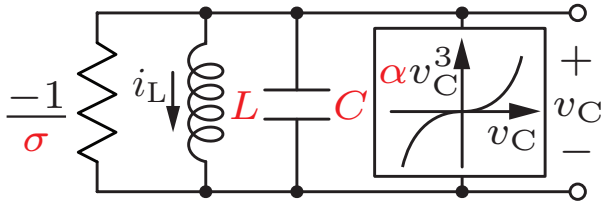


nominal frequency, high quality waveform, sluggish

Parameters chosen for $\varepsilon\sigma = 1$



nominal frequency, high quality waveform, fast



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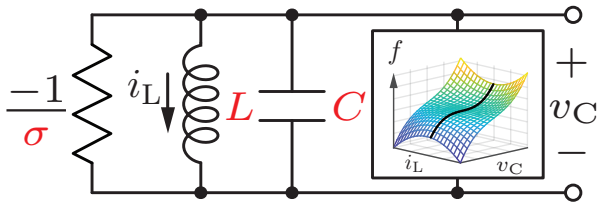
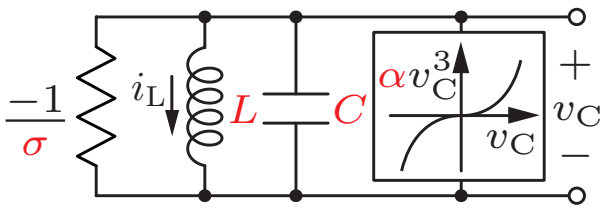


Circuit for Andronov

Revisiting the Wishlist

✓	✓	Works across high to zero inertia
✗	✓	Compatible in both grid-connected & islanded
✓	?	Robustly synchronizes in large networks
?	✓	Rapid convergence to steady state
✗	✓	Can act on exogenous setpoints
?	✓	Produces high quality voltage waveform
✓	✓	Controller has unambiguous design procedure
✓	✓	Integrated droop functions



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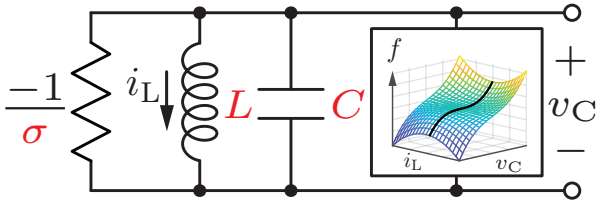
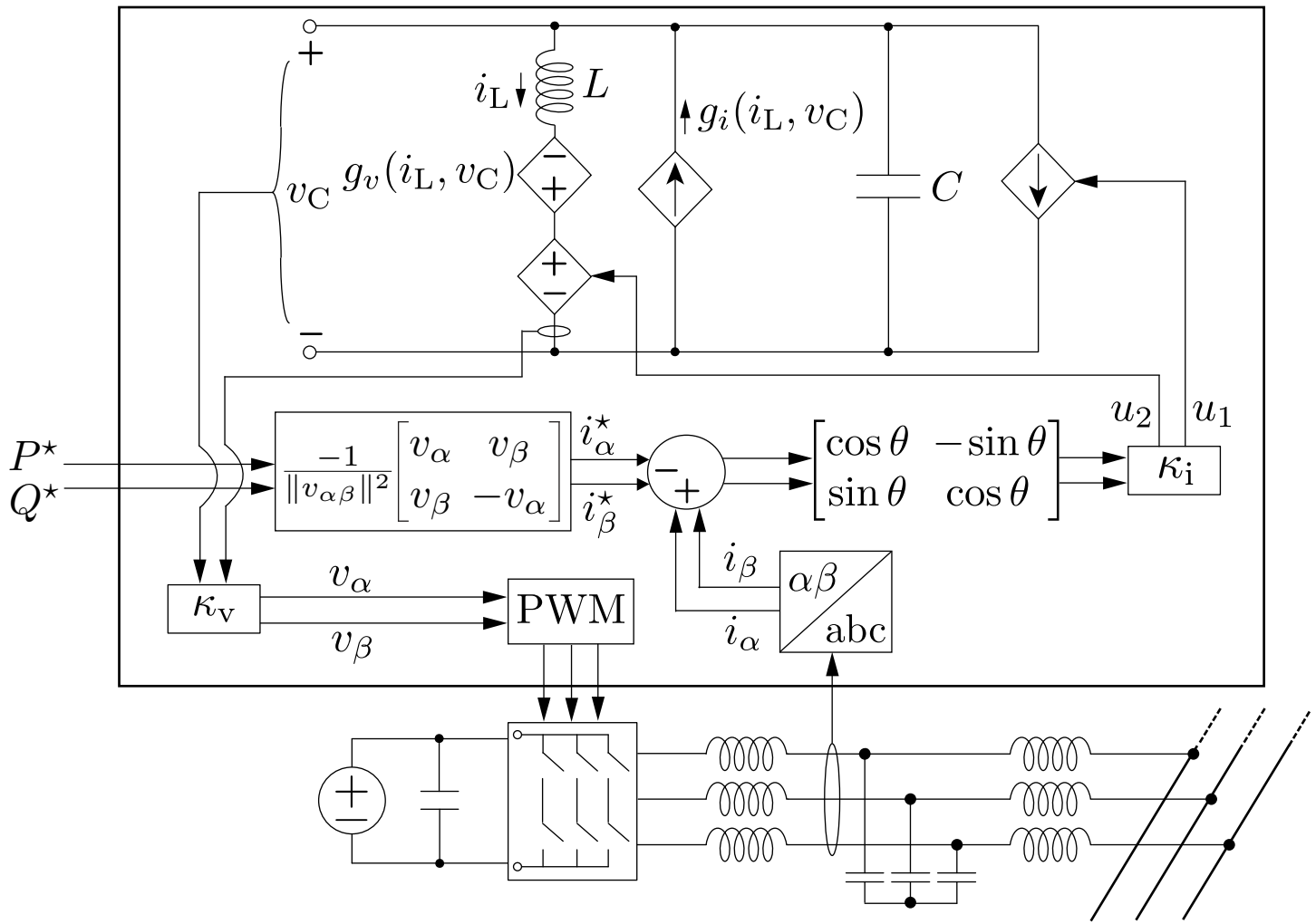
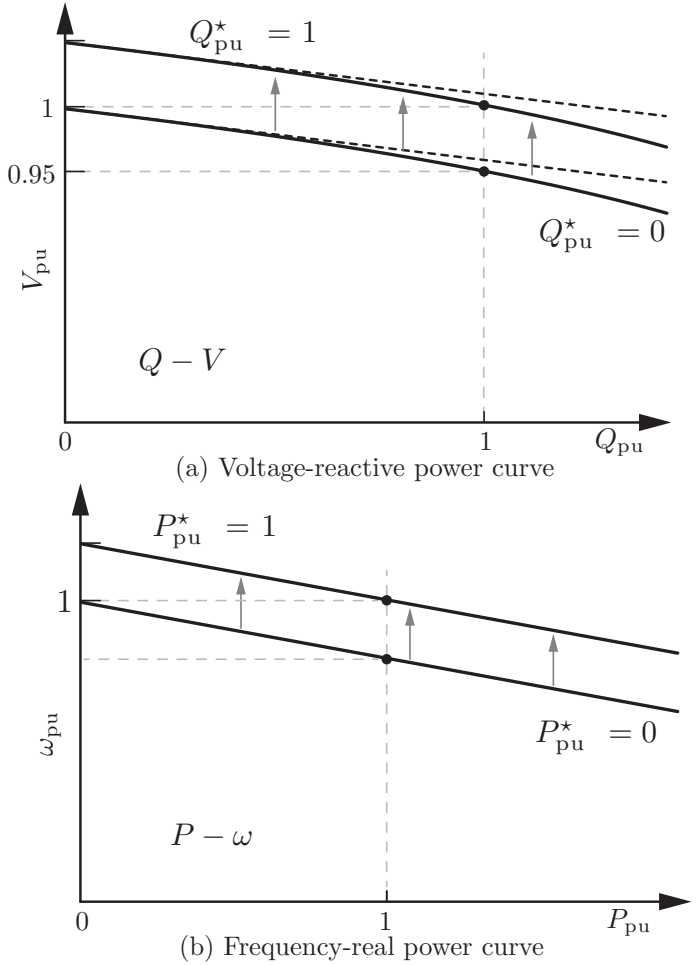


Circuit for Andronov

Practical Implementation on Hardware

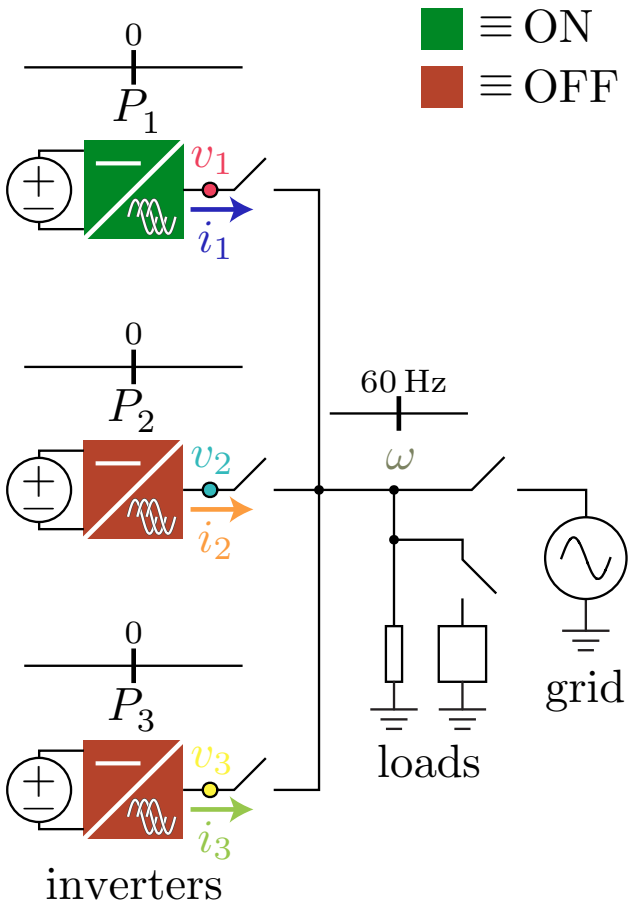




(a) Voltage-reactive power curve

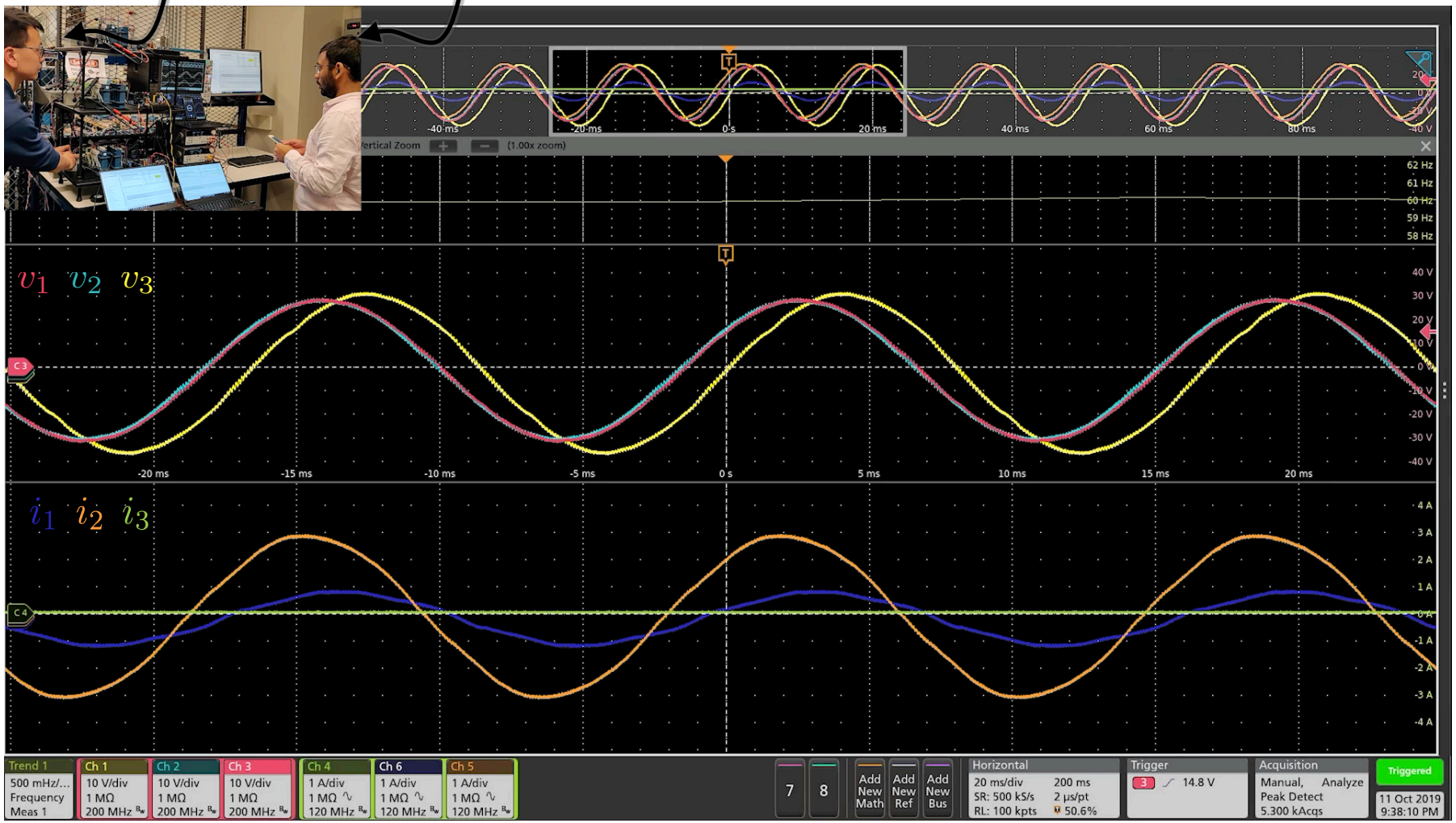
(b) Frequency-real power curve

Demo Description

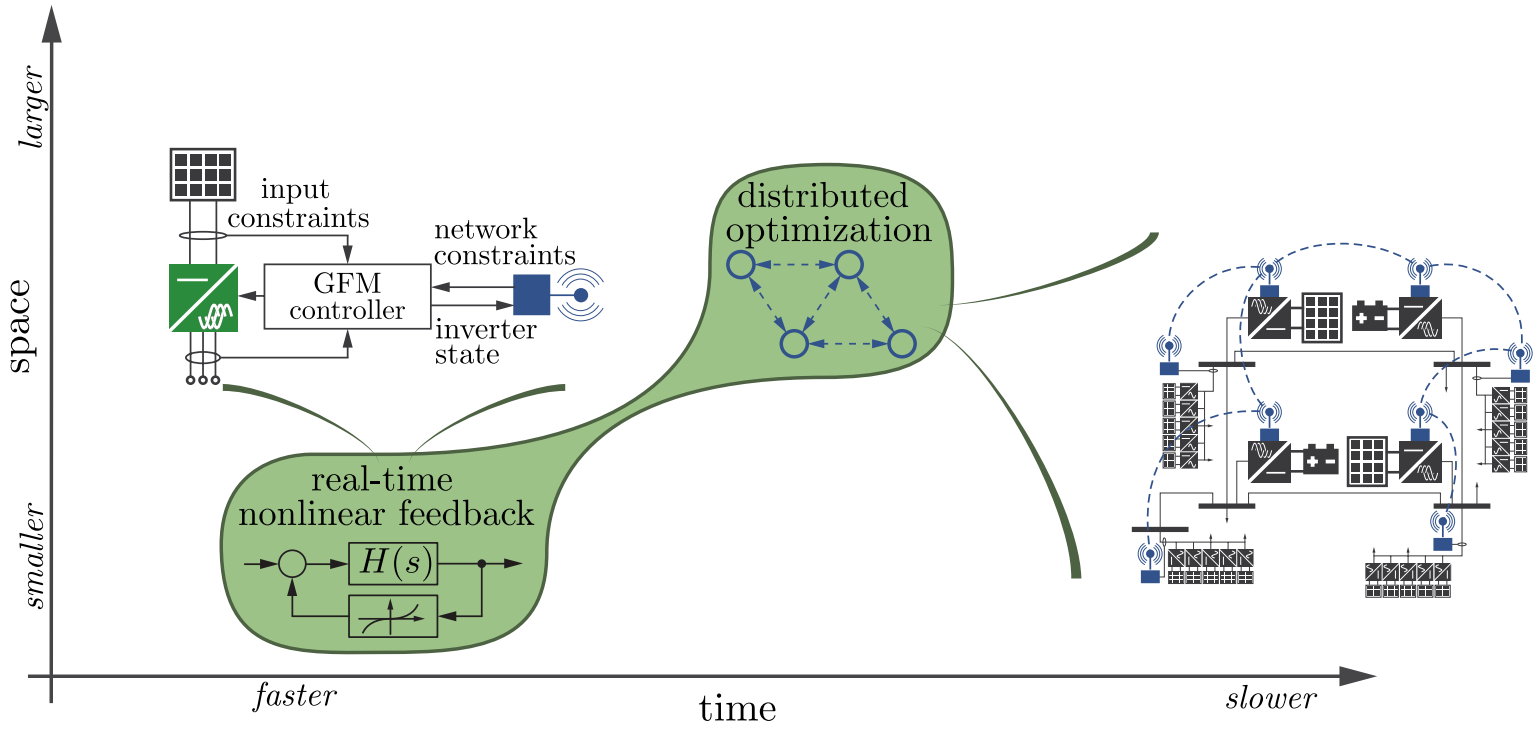


Captain:
Dr. Minghui Lu

First Officer:
Rahul Mallik



Future Innovations Needed for Power System Utilization



Partition controls by timescales

- Primary: Fast communication-free GFM controls for stabilization
- Secondary/Tertiary: Distributed controllers balance supply-demand

Thanks for your attention!