Nonlinear Decentralized Control for Future Grids

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The Future Grid

- Green: Grid Forming (GFM)
- Brown: Grid Following (GFL)
- Blue: Communication gateway
- Downward arrows: Loads
- Lines: Lines
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

Aleksandr Andronov
1901-1952

\[ \dot{x}_1 = \varepsilon \omega_0 (\sigma x_1 - \alpha \|x\|^2 x_1) - \omega_0 x_2, \]
\[ \dot{x}_2 = \omega_0 x_1. \]
Circuit Interpretations of Nonlinear Oscillators

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

\[ \downarrow \]

\[ C \frac{dv_C}{dt} = -i_L - \alpha v_C^3 + \sigma v_C, \]
\[ L \frac{di_L}{dt} = v_C, \]

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

\[ \downarrow \]

\[ \text{Circuit for van der Pol} \]

\[ \dot{x}_1 = \varepsilon \omega_0 (\sigma x_1 - \alpha \|x\|^2 x_1) - \omega_0 x_2, \]
\[ \dot{x}_2 = \omega_0 x_1. \]

\[ \downarrow \]

\[ C \frac{dv_C}{dt} = -i_L - \alpha (v_C^2 + \varepsilon^2 i_L^2) v_C + \sigma v_C, \]
\[ L \frac{di_L}{dt} = v_C, \]

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

\[ \downarrow \]

\[ \text{Circuit for Andronov} \]
Oscillator Design

nonlinear VOC system

VOC parameters:
\( \sigma, L, C, \alpha, \ldots \)

performance criteria:
- voltage regulation
- frequency regulation
- dynamic response
- harmonics limits

harmonics

averaged polar model

\[ |V| \quad \omega \]

perturbation methods

averaging methods

\[ \sigma, L, C, \alpha, \ldots \]
Key Parametric Relations

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

- frequency

\[ \tau_{\text{rise}} = \frac{6}{\varepsilon \sigma \omega_0} \]

- speed

\[ \frac{\text{third fundamental}}{\text{fundamental}} = \frac{\varepsilon \sigma}{8} \]

- harmonics

Circuit for van der Pol

Circuit for Andronov
Key Parametric Relations

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

frequency

\[ \omega = \omega_0 \]

speed

\[ t_{\text{rise}} = \frac{6}{\varepsilon \sigma \omega_0} \]

harmonics

\[ \begin{align*}
\frac{\text{third}}{\text{fundamental}} &= \frac{\varepsilon \sigma}{8} \\
\frac{\text{third}}{\text{fundamental}} &= 0
\end{align*} \]

Circuit for van der Pol

\[ \begin{align*}
-1 & \quad L \\
\sigma & \quad C \\
\alpha v_C^3 & \quad v_C
\end{align*} \]

Circuit for Andronov

\[ \begin{align*}
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\sigma & \quad C \\
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- Circuit for van der Pol

\[ \omega = \omega_0 \]

\[ t_{\text{rise}} = \frac{6}{\varepsilon \sigma \omega_0} \]

\[ \frac{\text{third}}{\text{fundamental}} = 0 \]

- Circuit for Andronov

Circuit for van der Pol

Circuit for Andronov
Dynamic Performance Comparison

Parameters chosen for $\varepsilon \sigma = 1$

- off-nominal frequency, low quality waveform, fast

- Circuit for van der Pol

Parameters chosen for $\varepsilon \sigma = 1$

- nominal frequency, high quality waveform, fast

- 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

Circuit for van der Pol

- Circuit for Andronov
Revisiting the Wishlist

<table>
<thead>
<tr>
<th>Feature</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Works across high to zero inertia</td>
<td>✓</td>
</tr>
<tr>
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<td>✓</td>
</tr>
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</table>

Circuit for van der Pol

Circuit for Andronov
Practical Implementation on Hardware

\[ P^* \]
\[ Q^* \]

\[ v_\alpha, v_\beta \]
\[ i_\alpha, i_\beta \]
\[ g_i(i_L, v_C) \]
\[ L \]
\[ C \]

\[ \frac{1}{\|v_{\alpha \beta}\|^2} \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \]
\[ \cos \theta \quad -\sin \theta \]
\[ \sin \theta \quad \cos \theta \]

\[ \alpha, \beta \]
\[ \text{abc} \]

Voltage-reactive power curve

(a) Voltage-reactive power curve

(b) Frequency-real power curve
Demo Description

Captain: Dr. Minghui Lu
First Officer: Rahul Mallik

\[ P_1, P_2, P_3 \]

\[ v_1, v_2, v_3 \]

\[ i_1, i_2, i_3 \]

\[ \omega = 60 \text{ Hz} \]

\[ 3 \text{ inverters} \]

\[ 3 \text{ loads} \]

\[ 3 \text{ grid} \]

\[ \text{Green: ON, Red: OFF} \]
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!