Control of Power Converters in Low-Inertia Power Systems

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NREL AES Workshop
Acknowledgements

Marcello Colombino
Ali Tayyebi-Khameneh
Dominic Groß
Irina Subotic

Further: A. Anta, J.S. Brouillon, G.S. Seo, B. Johnson, M. Sinha, & S. Dhople
Replacing the power system foundation

**fuel**
- not sustainable

**renewables**
+ sustainable
Replacing the power system foundation

**fuel**
- not sustainable
+ central & dispatchable generation

**renewables**
+ sustainable
- distributed & variable generation
Replacing the power system foundation

fuel & synchronous machines
- not sustainable
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renewables & power electronics
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Replacing the power system foundation

**fuel & synchronous machines**
- not sustainable
+ central & dispatchable generation
+ large rotational inertia as buffer

**renewables & power electronics**
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- distributed & variable generation
- almost no energy storage
Replacing the power system foundation

**fuel & synchronous machines**
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- large rotational inertia as buffer
- self-synchronize through the grid

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- distributed & variable generation
- almost no energy storage
- no inherent self-synchronization
Replacing the power system foundation

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- self-synchronize through the grid
- resilient voltage / frequency control

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- almost no energy storage
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- fragile voltage / frequency control
Replacing the power system foundation

**fuel & synchronous machines**
- not sustainable
- **central & dispatchable** generation
- **large** rotational **inertia** as buffer
- **self-synchronize** through the **grid**
- **resilient** voltage / frequency **control**
- slow actuation & **control**

**renewables & power electronics**
+ sustainable
- **distributed & variable** generation
- almost **no energy storage**
- no inherent **self-synchronization**
- **fragile** voltage / frequency **control**
+ fast / flexible / modular control
The concerns are not hypothetical

lack of robust control:

“Nine of the 13 wind farms online did not ride through the six voltage disturbances experienced during the event.”
The concerns are not hypothetical

**lack of robust control:**

“Nine of the 13 wind farms online did not ride through the six voltage disturbances experienced during the event.”

**between the lines:**

conventional system would have been more resilient (?)
The concerns are not hypothetical issues broadly recognized by TSOs, device manufacturers, academia, agencies, etc.

**UPDATE REPORT**

**BLACK SYSTEM EVENT**
**IN SOUTH AUSTRALIA ON**
**28 SEPTEMBER 2016**

**AN UPDATE TO THE PRELIMINARY OPERATING INCIDENT REPORT FOR THE NATIONAL ELECTRICITY MARKET.**
**DATA ANALYSIS AS AT 5.00 PM TUESDAY 11 OCTOBER 2016.**

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**ERCOT CONCEPT PAPER**

**Future Ancillary Services in ERCOT**

ERCOT is recommending the transition to the following five AS products plus one additional AS that would be used during some transition period:

1. Synchronous Inertial Response Service (SIR),
2. Fast Frequency Response Service (FFR),
3. Primary Frequency Response Service (PFR),
4. Up and Down Regulating Reserve Service (RR), and
5. Contingency Reserve Service (CR).

6. **Supplemental Reserve Service (SR)** (during transition period)

---

**Frequency Stability Evaluation Criteria for the Synchronous Zone of Continental Europe**

-- Requirements and impacting factors --

**RG-CE System Protection & Dynamics Sub Group**

However, as these sources are fully controllable, a regulation can be added to the inverter to provide “synthetic inertia”. This can also be seen as a short term frequency support. On the other hand, these sources might be quite restricted with respect to the available capacity and possible activation time. The inverters have a very low overload capability compared to synchronous machines.
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**obstacle to sustainability:**

power electronics integration
Foundations and Challenges of Low-Inertia Systems

(Invited Paper)

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The later sections contain many suggestions for further work, which can be summarized as follows:

- **New models** are needed which balance the need to include key features without burdening the model (whether for analytical or computational work) with uneven and excessive detail;

- **New stability theory** which properly reflects the new devices and time-scales associated with CIG, new loads and use of storage;

- Further **computational work** to achieve sensitivity guidelines including data-based approaches;

- **New control methodologies**, e.g. new controller to mitigate the high rate of change of frequency in low inertia systems;

- A power converter is a fully actuated, modular, and very fast control system, which are nearly antipodal characteristics to those of a synchronous machine. Thus, **one should critically reflect the control** of a converter as a virtual synchronous machine; and

- The lack of inertia in a power system does not need to (and cannot) be fixed by simply “adding inertia back” in the systems.
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**a key unresolved challenge**: control of power converters in low-inertia grids

→ industry & power community willing to explore **green-field approach** (see MIGRATE) with advanced control methods & theoretical certificates
Outline

Introduction: Low-Inertia Power Systems

Problem Setup: Modeling and Specifications

State of the Art: Comparison & Critical Evaluation

Dispatchable Virtual Oscillator Control

Comparison & Discussion
Basic modeling insights: the network

**interconnecting lines** via Π-models & ODEs

**conventional assumption:** quasi-steady state algebraic model

\[
\begin{pmatrix}
i_1 \\
\vdots \\
i_n
\end{pmatrix} = \begin{pmatrix}
y_{11} & \cdots & y_{1n} \\
\vdots & \ddots & \vdots \\
y_{n1} & \cdots & y_{nn}
\end{pmatrix} \begin{pmatrix}
-1 \\
\vdots \\
-1
\end{pmatrix}
\]

\[
\begin{pmatrix}
v_1 \\
\vdots \\
v_n
\end{pmatrix}
\]

Laplacian matrix with \(y_{kj} = \frac{1}{\text{complex impedance}}\)

**salient feature:** local measurement reveals synchronizing coupling

\[
l_{ik} = \sum_{j=1}^{n} y_{kj} (v_k - v_j)
\]

**global synchronization**

**note:** quasi-steady-state assumption is flawed
Basic modeling insights: the network

**interconnecting lines** via \( \Pi \)-models & ODEs

▶ **conventional assumption:** quasi-steady state algebraic model

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\begin{bmatrix}
i_1 \\
\vdots \\
i_n
\end{bmatrix}
= \begin{bmatrix}
- y_{k1} & \cdots & \sum_{j=1}^{n} y_{kj} & \cdots & - y_{kn} \\
\vdots & \ddots & \vdots & \ddots & \vdots \\
\vdots & & \vdots & & \vdots \\
- y_{kn} & & - y_{kn} & & - y_{kn}
\end{bmatrix}
\begin{bmatrix}
v_1 \\
\vdots \\
v_n
\end{bmatrix}
\]

nodal injections  \hspace{1cm} \text{Laplacian matrix with } y_{k,j} = 1/ \text{complex impedance}  \hspace{1cm} \text{nodal potentials}

▶ **salient feature:** local measurement reveals synchronizing coupling

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5
Basic modeling insights: the network

interconnecting lines via Π-models & ODEs

▶ conventional assumption: quasi-steady state algebraic model

\[
\begin{bmatrix}
  i_1 \\
  \vdots \\
  i_n
\end{bmatrix} = \begin{bmatrix}
  \vdots & \vdots & \vdots & \vdots \\
  -y_{k1} & \sum_{j=1}^{n} y_{kj} & \vdots & \vdots \\
  \vdots & \vdots & \ddots & \vdots \\
  \vdots & \vdots & \vdots & -y_{kn}
\end{bmatrix} \begin{bmatrix}
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  \vdots \\
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\end{bmatrix}
\]

Laplacian matrix with \( y_{kj} = 1 / \text{complex impedance} \)

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local variable

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note: quasi-steady-state assumption is flawed in low-inertia systems
Basic modeling insights: the network

**interconnecting lines** via Π-models & ODEs

▶ conventional assumption: quasi-steady state **algebraic model**

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v_1 \\
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- nodal injections
- Laplacian matrix with \( y_{kj} = 1 / \text{complex impedance} \)
- nodal potentials

▶ salient feature: **local** measurement reveals **synchronizing** coupling

\[
i_k = \sum_j y_{kj} (v_k - v_j)
\]

- local variable
- global synchronization

▶ note: quasi-steady-state **assumption is flawed** in low-inertia systems
Basic modeling insights: the power converter

DC port modulation control (3-phase) LC output filter AC port to power grid

\[ \text{L, R, G, C} \]

network
Basic modeling insights: the power converter

- **passive DC port** port \((i_{dc}, v_{dc})\) for energy balance control
  - details mostly neglected today: assume \(v_{dc}\) to be stiffly regulated

- **modulation** \(\equiv\) lossless signal transformer (averaged)
  - controlled switching voltage \(v_{dc}m\) with \(m \in [-\frac{1}{2}, \frac{1}{2}] \times [-\frac{1}{2}, \frac{1}{2}]\)

- **LC filter** to smoothen harmonics with \(R, G\) modeling filter/switching losses
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- **LC filter** to smoothen harmonics with \(R, G\) modeling filter/switching losses

well actuated, modular, & fast control system \(\approx\) **controllable voltage source**
Objectives for power converter control

1. *synchronous frequency*

\[
\frac{d}{dt} v_k = \begin{bmatrix} 0 & -\omega_0 \\ \omega_0 & 0 \end{bmatrix} v_k
\]

\sim \text{harmonic oscillations at identical } \omega_0
Objectives for power converter control

1. **synchronous frequency**

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\sim \text{harmonic oscillations at identical } \omega_0

2. **voltage amplitude**

\[
\|v_k\| = v_k^*
\]
Objectives for power converter control

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\( \sim \) harmonic oscillations at identical \( \omega_0 \)

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\[ \|v_k\| = v^* \]

\( \sim \) \( v^* \) uniform for ease of presentation
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2. **voltage amplitude**
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   \(\sim\) \(v^*\) uniform for ease of presentation

3. **active & reactive power injections**
   \[
   v_k^\top i_{o,k} = p_k^* , \quad v_k^\top \begin{bmatrix} 0 & -1 \\ +1 & 0 \end{bmatrix} i_{o,k} = q_k^*
   \]
   \(\sim\) non-linear but local specification
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\[\iff\] **relative voltage angles**
\[v_k = \begin{bmatrix} \cos(\theta_{jk}^*) & -\sin(\theta_{jk}^*) \\ \sin(\theta_{jk}^*) & \cos(\theta_{jk}^*) \end{bmatrix} v_j\]
\[\sim\] linear but non-local specification
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≈ linear but non-local specification
Main control challenges

Nonlinear objectives $(v^*_k, \theta^*_{jk})$ & stabilization of synchronous limit cycle

Intrinsic synchronization to $\omega_0$ rather than following weak grid frequency

Local set-points: voltage / power $(v^*_k, p^*_k, q^*_k)$ but no relative angles $\theta^*_{jk}$

Decentralized control: only local measurements $(v_k, i_{o,k})$ available

Fragile physics needs tight control: state constraints & negligible storage

No time-scale separation between slow sources & fast network + fully controllable voltage sources & stable linear network dynamics
Main control challenges

- **Nonlinear objectives** \((v^*_k, \theta^*_{k,j})\) & stabilization of synchronous **limit cycle**
Main control challenges

\[ \omega \ast jk \omega k \omega j \omega \ast k \omega 0 \omega 0 \]

- \textit{nonlinear objectives} \((v_k^*, \theta_{jk}^*)\) & stabilization of synchronous \textit{limit cycle}
- \textit{intrinsic synchronization} to \(\omega_0\) rather than following weak grid frequency

\[ C \]

\[ v_{dc} \]

\[ v_{o,k} \]
Main control challenges

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- **no time-scale separation** between slow sources & fast network
- **fully controllable** voltage sources & stable linear network dynamics
Naive baseline solution: emulation of virtual inertia
Cartoon of low-level power converter control

1. acquiring & processing of **AC measurements**
2. synthesis of **references**
   “how would a synchronous generator respond now?”
3. cascaded PI controllers to **track** references
   **assumption:** no state constraints encountered
4. **actuation** via modulation
5. **energy balancing** via fast control of DC-side supply
   **assumption:** unlimited power & instantaneous
Virtual synchronous machine ≡ flywheel emulation

- **reference model**: detailed model of synchronous generator + controls
Virtual synchronous machine ≡ flywheel emulation

- **reference model**: detailed model of synchronous generator + controls
- robust **implementation** requires tricks: low-pass filters for dissipation, virtual impedances for saturation, limiters, ...

[D'Arco et al., '15]
Virtual synchronous machine $\equiv$ flywheel emulation

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$\rightarrow$ most commonly accepted solution in industry (§ backward compatibility?)

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[D'Arco et al., '15]
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\[ \rightarrow \] most commonly accepted solution in industry (\& backward compatibility ?)

\[ \rightarrow \] **poor fit**: converter \( \neq \) flywheel
  - converter: fast actuation & **no** significant energy storage
  - machine: slow actuation & significant energy storage

\[ \rightarrow \] over-parametrized & ignores limits

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→ **poor fit**: converter ≠ flywheel
  - converter: **fast** actuation & no significant **energy storage**
  - machine: **slow** actuation & significant **energy storage**

→ **over-parametrized** & ignores **limits**

→ **performs very poorly** post-fault

[D'Arco et al., '15]
Droop as simplest reference model

- **frequency control** by mimicking $p - \omega$ droop property of synchronous machine:

  $$\omega - \omega_0 \propto p - p^*$$
Droop as simplest reference model

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  $$\frac{d}{dt} \|v\| = -c_1 (\|v\| - v^*) - c_2 (q - q^*)$$
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- **reference** are generator controls

  → direct control of $(p, \omega)$ and $(q, \|v\|)$ assuming they are independent (approx. true only near steady state)
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  → requires **tricks in implementation**: similar to virtual synchronous machine
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  - Requires **tricks in implementation**
    - Similar to virtual synchronous machine

  - **Good small-signal** but poor large signal behavior (region of attraction)
Original Virtual Oscillator Control (VOC)

nonlinear & open limit cycle oscillator as reference model

[J. Aracil & F. Gordillo, ’02], [Torres, Hespanha, Moehlis, ’11],
[Johnson, Dhople, Krein, ’13], [Dhople, Johnson, Dörfler, ’14]
**Original Virtual Oscillator Control (VOC)**

**nonlinear & open limit cycle oscillator** as reference model

![Diagram of a nonlinear & open limit cycle oscillator](image)

\[ g(v) + \omega v - \omega(v) \]

\[ g(v) \]

\[ v \]

\[ \omega(v) \]

\[ i_o \]

[Simplified model amenable to theoretic analysis → almost global synchronization & local droop]

- In practice proven to be a robust mechanism with performance superior to droop & others
- Problem: cannot be controlled to meet specifications on amplitude & power injections

[J. Aracil & F. Gordillo, '02], [Torres, Hespanha, Moehlis, '11], [Johnson, Dhople, Krein, '13], [Dhople, Johnson, Dörfler, '14]
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Comparison of grid-forming control [Tayyebi et al., '19]

**droop control**

- good performance near steady state
- relies on decoupling & small attraction basin

**synchronous machine emulation**

- backward compatible in nominal case
- not resilient under large disturbances

**virtual oscillator control (VOC)**

- robust & almost globally synchronization
- cannot meet amplitude/power specifications
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- robust & almost globally synchronization
- cannot meet amplitude/power specifications

**today:** dispatchable virtual oscillator

[Colombino, Groß, Brouillon, & Dörfler, '17, '18, '19]
[Seo, Subotic, Johnson, Colombino, Groß, & Dörfler, '19]
Model & control objectives

(simplified multi-converter system model)

➤ converter = terminal voltage $u_k \in \mathbb{R}^2$
Model & control objectives

(assumptions can all be generalized)

simplified multi-converter system model

- converter = terminal voltage $v_k \in \mathbb{R}^2$
- line dynamics = steady-state $\Pi$-model with line admittance $\|Y_{jk}\| = \frac{1}{\sqrt{r_{kj}^2 + \omega_0^2 \ell_{kj}^2}}$

DC port modulation control (3-phase) LC output filter AC port to power grid

$\omega_{dc}$

$\omega_{dc}$

$v_{dc}$

$i_L$

$R$

$L$

$C$

$G$

$i_o$

$\mathbf{v}$

$\mathbf{u}$

$\mathbf{m}$

$\omega_0$

$\ell_{kj}$

$r_{kj}$

$\kappa$

$\Delta$

$\mathbf{v}_k$

$\mathbf{p}^\star_k$

$\mathbf{q}^\star_k$

$\Delta$

$\mathbf{v}_j$

$\mathbf{v}_k$

$\theta^\star_{jk}$

$\theta^\star_{jk}$

$\omega^\star_{jk}$

$\omega^\star_k$

$\omega^\star_j$
Model & control objectives

(assumptions can all be generalized)

**simplified multi-converter system model**

- **converter** = terminal voltage $v_k \in \mathbb{R}^2$
- **line dynamics** = steady-state Π-model with line admittance $\|Y_{jk}\| = 1/\sqrt{r_{kj}^2 + \omega_0^2\ell_{kj}^2}$
- **homogeneous lines** with $\kappa = \frac{\ell_{jk}}{r_{jk}}$ constant
Model & control objectives
(assumptions can all be generalized)

**simplified multi-converter system model**

- **converter** = terminal voltage \( v_k \in \mathbb{R}^2 \)
- **line dynamics** = steady-state II-model with line admittance \( \|Y_{jk}\| = \frac{1}{\sqrt{r^2_{kj} + \omega_0^2 \ell^2_{kj}}} \)
- **homogeneous lines** with \( \kappa = \frac{\ell_{jk}}{r_{jk}} \) constant

**desired steady-state behavior**
Model & control objectives

(assumptions can all be generalized)

simplified multi-converter system model

- converter = terminal voltage $v_k \in \mathbb{R}^2$
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- homogeneous lines with $\kappa = \frac{\ell_{jk}}{r_{jk}}$ constant

desired steady-state behavior

- nominal synchronous frequency
  \[
  \frac{d}{dt} v_k = \begin{bmatrix} 0 & -\omega_0 \\ \omega_0 & 0 \end{bmatrix} v_k
  \]
Model & control objectives

(situations can all be generalized)

**simplified multi-converter system model**

- converter = terminal voltage $v_k \in \mathbb{R}^2$
- line dynamics = steady-state II-model with line admittance $\|Y_{jk}\| = 1/\sqrt{r_{k,j}^2 + \omega_0^2\ell_{k,j}^2}$
- homogeneous lines with $\kappa = \frac{\ell_{j,k}}{r_{j,k}}$ constant

**desired steady-state behavior**

- nominal synchronous frequency

\[
\frac{d}{dt} v_k = \begin{bmatrix} 0 & -\omega_0 \\ \omega_0 & 0 \end{bmatrix} v_k
\]

- voltage amplitude (uniform for this talk)

\[
\|v_k\| = v^* 
\]
Model & control objectives  
(assumptions can all be generalized)

**simplified multi-converter system model**

- **converter** = terminal voltage $\mathbf{v}_k \in \mathbb{R}^2$
- **line dynamics** = steady-state II-model with line admittance $\|Y_{jk}\| = \frac{1}{\sqrt{r_{kj}^2 + \omega_0^2\ell_{kj}^2}}$
- **homogeneous lines** with $\kappa = \frac{\ell_{jk}}{r_{jk}}$ constant

**desired steady-state behavior**

- **nominal synchronous frequency**
  \[
  \frac{d}{dt} \mathbf{v}_k = \begin{bmatrix} 0 & -\omega_0 \\ \omega_0 & 0 \end{bmatrix} \mathbf{v}_k
  \]

- **voltage amplitude** (uniform for this talk)
  $\|\mathbf{v}_k\| = v^*$

- **active & reactive power injections**
  $\mathbf{v}_k^\top \mathbf{i}_{o,k} = P_k^*$,  $\mathbf{v}_k^\top \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \mathbf{i}_{o,k} = q_k^*$
Model & control objectives  
(assumptions can all be generalized)

simplified multi-converter system model

- **converter** = terminal voltage $v_k \in \mathbb{R}^2$
- **line dynamics** = steady-state II-model with line admittance $\|Y_{jk}\| = 1/\sqrt{r_{kj}^2 + \omega_0^2 \ell_{kj}^2}$
- **homogeneous lines** with $\kappa = \frac{\ell_{jk}}{r_{jk}}$ constant

desired steady-state behavior

- **nominal synchronous frequency**
  \[
  \frac{d}{dt} v_k = \begin{bmatrix} 0 & -\omega_0 \\ \omega_0 & 0 \end{bmatrix} v_k
  \]

- **voltage amplitude**  (uniform for this talk)
  \[
  \|v_k\| = v^*
  \]

- **active & reactive power injections**
  \[
  v_k^\top i_{o,k} = p_k^*, \quad v_k^\top \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} i_{o,k} = q_k^*
  \]

\[\iff\] relative angles:
  \[
  v_j = \begin{bmatrix} \cos(\theta_{jk}^*) & -\sin(\theta_{jk}^*) \\ \sin(\theta_{jk}^*) & \cos(\theta_{jk}^*) \end{bmatrix} v_k
  \]
Colorful idea: closed-loop target dynamics

\[
\frac{dv_k}{dt} = \begin{bmatrix} 0 & -\omega_0 & 0 \\ 0 & 0 & -\omega_0 \\ 0 & 0 & 0 \end{bmatrix} v_k + \omega_0 \omega_0 \cdot (\|v_k\|_2^2 - \|v_k\|_2^2) v_k
\]

Rotation at \(\omega_0 + c_2 \cdot (\|v_k\|_2^2 - \|v_k\|_2^2) v_k\)

Amplitude regulation to \(v^*_k + c_1 \cdot n \sum_{j=1} v_{jk} (v_j - [\cos(\theta^*_jk) \sin(\theta^*_jk), -\sin(\theta^*_jk) \cos(\theta^*_jk)]) v_k)\)

Synchronization to desired relative angles \(\theta^*_jk\)
Colorful idea: closed-loop target dynamics

\[ d\frac{dt}{dt} v_k = \begin{bmatrix} 0 & -\omega_0 & 0 \\ -\omega_0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} v_k \]

\[ \theta_{jk}^* = \begin{bmatrix} \cos(\theta_{jk}^*) & -\sin(\theta_{jk}^*) \\ \sin(\theta_{jk}^*) & \cos(\theta_{jk}^*) \end{bmatrix} v_k \]

\[ v_k^* = v_k + c_1 \sum_{j=1}^n w_{jk} (v_j - \theta_{jk}^*) \]

\[ \omega_0 \]

\[ \omega_0 \]

\[ v_k \]

\[ v_j \]
Colorful idea: closed-loop target dynamics

\[
\frac{d}{dt} \mathbf{v}_k = \begin{bmatrix} 0 & -\omega_0 \\ \omega_0 & 0 \end{bmatrix} \mathbf{v}_k + c_2 \cdot (\|\mathbf{v}_k\|^2 - \|\mathbf{v}_k^*\|^2) \mathbf{v}_k
\]
- rotation at \(\omega\)
- amplitude regulation to \(v_k^*\)

\[
+ c_1 \cdot \sum_{j=1}^{n} w_{jk} \left( \mathbf{v}_j - \begin{bmatrix} \cos(\theta_{jk}^*) & -\sin(\theta_{jk}^*) \\ \sin(\theta_{jk}^*) & \cos(\theta_{jk}^*) \end{bmatrix} \mathbf{v}_k \right)
\]
- synchronization to desired relative angles \(\theta_{jk}^*\)
Decentralized implementation of dynamics

\[ \sum_j w_{jk} (v_j - R(\theta^*_{jk})v_k) \]

need to know \( w_{jk}, v_j, v_k \) and \( \theta^*_{jk} \).
Decentralized implementation of dynamics

\[ \sum_j w_{jk}(v_j - R(\theta^*_j) v_k) = \sum_j w_{jk}(v_j - v_k) + \sum_j w_{jk}(I - R(\theta^*_j)) v_k \]

need to know \( w_{jk}, v_j, v_k \) and \( \theta^*_j \)

“Laplacian” feedback

local feedback: \( K_k(\theta^*) v_k \)
Decentralized implementation of dynamics

\[ \sum_j w_{jk} (v_j - R(\theta^*_j) v_k) = \sum_j w_{jk} (v_j - v_k) + \sum_j w_{jk} (I - R(\theta^*_j)) v_k \]

need to know \( w_{jk}, v_j, v_k \) and \( \theta^*_j \)  

“Laplacian” feedback  
local feedback: \( \mathcal{K}_k(\theta^*) v_k \)

\textit{insight I: non-local measurements from} communication via physics

\[ \dot{i}_{o,k} = \sum_j y_{jk} (v_j - v_k) \]

local feedback  
distributed feedback with \( w_{jk} = y_{kj} = \|y_{kj}\| R(\kappa)^{-1} \)
Decentralized implementation of dynamics

\[ \sum_j w_{jk} (v_j - R(\theta^*_{jk}) v_k) = \sum_j w_{jk} (v_j - v_k) + \sum_j w_{jk} (I - R(\theta^*_{jk})) v_k \]

need to know \( w_{jk}, v_j, v_k \) and \( \theta^*_{jk} \)  

“Laplacian” feedback  

local feedback: \( K_k(\theta^*) v_k \)

**insight I**: non-local measurements from **communication via physics**

\[ i_{o,k} = \sum_j y_{jk} (v_j - v_k) \]

distributed feedback with \( w_{jk} = y_{kj} = \| y_{kj} \| R(\kappa)^{-1} \)

**insight II**: angle set-points & line-parameters from **power flow equations**

\[ p^*_k = v^* \sqrt{2} \sum_j \frac{r_{jk}(1-\cos(\theta^*_{jk}))-\omega_0 \ell_{jk} \sin(\theta^*_{jk})}{r_{jk}^2 + \omega_0^2 \ell_{jk}^2} \]

\[ q^*_k = -v^* \sqrt{2} \sum_j \frac{\omega_0 \ell_{jk}(1-\cos(\theta^*_{jk}))+r_{jk} \sin(\theta^*_{jk})}{r_{jk}^2 + \omega_0^2 \ell_{jk}^2} \]
Decentralized implementation of dynamics

\[ \sum_j w_{jk} (v_j - R(\theta^*_j) v_k) = \underbrace{\sum_j w_{jk} (v_j - v_k)}_{\text{Laplacian feedback}} + \underbrace{\sum_j w_{jk} (I - R(\theta^*_j)) v_k}_{\text{local feedback: } K_k(\theta^*) v_k} \]

need to know \( w_{jk}, v_j, v_k \) and \( \theta^*_j \)

**Insight I:** non-local measurements from communication via physics

\[ \dot{i}_{o,k} = \sum_j y_{jk} (v_j - v_k) \]

local feedback distributed feedback with \( w_{jk} = y_{kj} = \| y_{kj} \| R(\kappa)^{-1} \)

**Insight II:** angle set-points & line-parameters from power flow equations

\[ \begin{aligned} &p_k^* = v^* \sum_j r_{jk} \frac{(1 - \cos(\theta^*_j)) - \omega_0 \ell_j \sin(\theta^*_j)}{r_{jk}^2 + \omega_0^2 \ell_{jk}^2} \\ &q_k^* = -v^* \sum_j \frac{\omega_0 \ell_j (1 - \cos(\theta^*_j)) + r_{jk} \sin(\theta^*_j)}{r_{jk}^2 + \omega_0^2 \ell_{jk}^2} \end{aligned} \]

\[ \Rightarrow K_k(\theta^*) = \frac{1}{v^*} R(\kappa) \begin{bmatrix} q_k^* \\ -p_k^* \end{bmatrix} \]

\[ K_k(\theta^*) \]

\[ \begin{bmatrix} q_k^* \\ -p_k^* \end{bmatrix} \]

global parameters local parameters
Properties of virtual oscillator control

1. desired target dynamics can be realized via **fully decentralized control**

\[
\frac{d}{dt} v_k = \begin{bmatrix} 0 & -\omega_0 \\ \omega_0 & 0 \end{bmatrix} v_k + c_1 \cdot R(\kappa) \left( \frac{1}{v^2} \begin{bmatrix} q_k^* & p_k^* \\ -p_k^* & q_k^* \end{bmatrix} v_k - i_{o,k} \right) + c_2 \cdot (v^2 - \|v_k\|^2) v_k
\]

- rotation at \( \omega_0 \)
- synchronization through physics
- local amplitude regulation
Properties of virtual oscillator control

1. desired target dynamics can be realized via **fully decentralized control**

\[
\frac{d}{dt} v_k = \begin{bmatrix} 0 & -\omega_0 \\ \omega_0 & 0 \end{bmatrix} v_k + c_1 \cdot R(\kappa) \left( \frac{1}{v^{\star 2}} \begin{bmatrix} q_k^\star & p_k^\star \\ -p_k^\star & q_k^\star \end{bmatrix} v_k - i_{o,k} \right) + c_2 \cdot (v^{\star 2} - ||v_k||^2) v_k
\]

- rotation at \( \omega_0 \)
- synchronization through physics
- local amplitude regulation

2. connection to **droop control** revealed in polar coordinates (for inductive grid)

\[
\frac{d}{dt} \theta_k = \dot{\omega}_0 + c_1 \left( \frac{p_k^\star}{v^{\star 2}} - \frac{p_k}{||v_k||^2} \right)
\]
Properties of virtual oscillator control

1. desired target dynamics can be realized via **fully decentralized control**

\[
\frac{d}{dt} v_k = \begin{bmatrix} 0 & -\omega_0 \\ \omega_0 & 0 \end{bmatrix} v_k + c_1 \cdot R(\kappa) \left( \frac{1}{v^*} \begin{bmatrix} q_k^* & p_k^* \\ -p_k^* & q_k^* \end{bmatrix} v_k - i_{o,k} \right) + c_2 \cdot (v^* - ||v_k||^2) v_k
\]

- rotation at \( \omega_0 \)
- synchronization through physics
- local amplitude regulation

2. connection to **droop control** revealed in polar coordinates (for inductive grid)

\[
\frac{d}{dt} \theta_k = \omega_0 + c_1 \left( \frac{p_k^*}{v^*} - \frac{p_k}{||v_k||^2} \right) ||v_k|| \approx 1 \omega_0 + c_1 \left( p_k^* - p_k \right) (p - \omega \text{ droop})
\]
Properties of virtual oscillator control

1. desired target dynamics can be realized via **fully decentralized control**

\[
\frac{d}{dt} v_k = \begin{bmatrix} 0 & -\omega_0 \\ \omega_0 & 0 \end{bmatrix} v_k + c_1 \cdot R(\kappa) \left( \frac{1}{v^*} \begin{bmatrix} q_0^* & p_0^* \\ -p_0^* & q_0^* \end{bmatrix} v_k - i_{o,k} \right) + c_2 \cdot (v^* - \|v_k\|^2) v_k
\]

- rotation at \( \omega_0 \)
- synchronization through physics
- local amplitude regulation

2. connection to **droop control** revealed in polar coordinates (for inductive grid)

\[
\frac{d}{dt} \theta_k = \omega_0 + c_1 \left( \frac{p_k^*}{v^*} - \frac{p_k}{\|v_k\|^2} \right) \cdot \|v_k\| \approx 1 \quad \omega_0 + c_1 \left( p_k^* - p_k \right) \left( p - \omega \text{ droop} \right)
\]

\[
\frac{d}{dt} \|v_k\|
\]
Properties of virtual oscillator control

1. desired target dynamics can be realized via **fully decentralized control**

\[
\frac{d}{dt} v_k = \begin{bmatrix} 0 & -\omega_0 \\ \omega_0 & 0 \end{bmatrix} v_k + c_1 \cdot R(\kappa) \left( \frac{1}{|v|^2} \begin{bmatrix} q_k^* & p_k^* \\ -p_k^* & q_k^* \end{bmatrix} v_k - i_{o,k} \right) + c_2 \cdot (|v|^2 - \|v_k\|^2) v_k
\]

- rotation at \(\omega_0\)
- synchronization through physics
- local amplitude regulation

2. connection to **droop control** revealed in polar coordinates (for inductive grid)

\[
\frac{d}{dt} \theta_k = \omega_0 + c_1 \left( \frac{p_k^*}{|v|^2} - \frac{p_k}{\|v_k\|^2} \right) \|v_k\| \approx 1 \approx \omega_0 + c_1 \left( p_k^* - p_k \right) (p - \omega \text{ droop})
\]

\[
\frac{d}{dt} \|v_k\| \approx c_1 \left( q_k^* - q_k \right) + c_2 \left( |v|^* - \|v_k\| \right) \approx 1 \quad (q - \|v\| \text{ droop})
\]
Properties of virtual oscillator control

1. desired target dynamics can be realized via **fully decentralized control**

\[
\frac{d}{dt} \mathbf{v}_k = \begin{bmatrix} 0 & -\omega_0 \\ \omega_0 & 0 \end{bmatrix} \mathbf{v}_k + c_1 \cdot \mathbf{R} (\kappa) \left( \frac{1}{\mathbf{v}^*} \left[ \begin{array}{cc} q_k^* & p_k^* \\ -p_k^* & q_k^* \end{array} \right] \mathbf{v}_k - \mathbf{i}_{o,k} \right) + c_2 \cdot \left( \mathbf{v}^* - \| \mathbf{v}_k \|^2 \right) \mathbf{v}_k 
\]

- rotation at \( \omega_0 \)
- synchronization through physics
- local amplitude regulation

2. connection to **droop control** revealed in polar coordinates (for inductive grid)

\[
\frac{d}{dt} \theta_k = \omega_0 + c_1 \left( \frac{p_k^*}{\mathbf{v}^*} - \frac{p_k}{\| \mathbf{v}_k \|^2} \right) \| \mathbf{v}_k \| \approx 1 \quad \omega_0 + c_1 \left( p_k^* - p_k \right) \left( p - \omega \text{ droop} \right)
\]

\[
\frac{d}{dt} \| \mathbf{v}_k \| \| \mathbf{v}_k \| \approx 1 \quad c_1 \left( q_k^* - q_k \right) + c_2 \left( \mathbf{v}^* - \| \mathbf{v}_k \| \right) \left( q - \| \mathbf{v} \| \text{ droop} \right)
\]

3. **almost global asymptotic stability** with respect to pre-specified set-point if
Properties of virtual oscillator control

1. desired target dynamics can be realized via **fully decentralized control**

\[
\frac{d}{dt} v_k = \begin{bmatrix} 0 & -\omega_0 \\ \omega_0 & 0 \end{bmatrix} v_k + c_1 \cdot R(\kappa) \left( \frac{1}{v^*} \begin{bmatrix} q^*_k & p^*_k \\ -p^*_k & q^*_k \end{bmatrix} v_k - i_{o,k} \right) + c_2 \cdot (u^* - ||v_k||^2) v_k
\]

- rotation at \( \omega_0 \)
- synchronization through physics
- local amplitude regulation

2. connection to **droop control** revealed in polar coordinates (for inductive grid)

\[
\frac{d}{dt} \theta_k = \omega_0 + c_1 \left( \frac{p^*_k}{v^*} - \frac{p_k}{||v_k||^2} \right) ||v_k|| \approx 1 \omega_0 + c_1 (p^*_k - p_k) (p - \omega \text{ droop})
\]

\[
\frac{d}{dt} ||v_k|| \approx 1 c_1 (q^*_k - q_k) + c_2 (u^* - ||v_k||) (q - ||v|| \text{ droop})
\]

3. **almost global asymptotic stability** with respect to pre-specified set-point if

- **power transfer** “small” compared to **network connectivity**
- **amplitude control** “slower” than **synchronization control**
Details on stability condition

- **power transfer** $p_{jk}$ “small” compared to **network connectivity** $\lambda_2$
- **amplitude control** “slower” than **synchronization control**: $c_2/c_1 \ll 1$

E.g., for resistive grid:

$$\frac{1}{2} \lambda_2 > \max_k \sum_{j=1}^{n} \frac{1}{v^*^2} |p_{jk}| + \frac{c_2}{c_1} v^*$$

- algebraic connectivity
- power transfer
Details on stability condition

- **power transfer** $p_{jk}$ “small” compared to **network connectivity** $\lambda_2$
- **amplitude control** “slower” than **synchronization control**: $c_2/c_1 \ll 1$

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- **conditions are exact** for two converters (or 0 set-points) & **approximately tight** in general
Details on stability condition

- **power transfer** $p_{jk}$ “small” compared to network connectivity $\lambda_2$
- **amplitude control** “slower” than synchronization control: $c_2/c_1 \ll 1$

\[
\frac{1}{2} \lambda_2 > \max_k \sum_{j=1}^{n} \frac{1}{v^*^2} |p_{jk}| + \frac{c_2}{c_1} v^*
\]

e.g., for resistive grid:

- **conditions are exact** for two converters (or 0 set-points) & **approximately tight** in general
Details on stability condition

- **power transfer** $p_{jk}$ “small” compared to **network connectivity** $\lambda_2$
- **amplitude control** “slower” than **synchronization control**: $c_2/c_1 \ll 1$

For resistive grid:

\[
\frac{1}{2} \lambda_2 > \max_k \sum_{j=1}^{n} \frac{1}{v^*^2} |p_{jk}| + \frac{c_2}{c_1} v^*
\]

- conditions are **exact** for two converters (or 0 set-points) & **approximately tight** in general
- proof relies on **Lyapunov arg’s**
Details on stability condition

- **Power transfer** $p_{jk}$ “small” compared to network connectivity $\lambda_2$
- **Amplitude control** “slower” than synchronization control: $c_2/c_1 \ll 1$

- \[ \frac{1}{2} \lambda_2 > \max_k \sum_{j=1}^n \frac{1}{v^*} \left| p_{jk} \right| + \frac{c_2}{c_1} v^* \]

  \text{e.g., for resistive grid:}

- $\lambda_2$\text{ algebraic connectivity}
- $\left| p_{jk} \right|$\text{ power transfer}

- \text{linear instability}
- \text{damping ratios}
- \text{certified stability region}

\[ \begin{array}{cccc}
0 & 5 & 10 & 15 & 20 \\
10^{-5} & 10^{-4} & 10^{-3} & \\
\hline
3 \cdot 10^{-2} & 6 \cdot 10^{-2} & 8 \cdot 10^{-2} & \\
6 \cdot 10^{-2} & 6 \cdot 10^{-2} & 8 \cdot 10^{-2} & \\
8 \cdot 10^{-2} & 8 \cdot 10^{-2} & 8 \cdot 10^{-2} & \\
9.5 \cdot 10^{-2} & 9.5 \cdot 10^{-2} & 9.5 \cdot 10^{-2} & \\
\end{array} \]

- **Conditions are exact** for two converters (or 0 set-points) & approximately tight in general
- **Proof relies on Lyapunov arg’s**
- **Conditions can be extended** to line dynamics, LC filter, & inner loops \cite{Subotic, Gross, Colombino, & Dörfler,'19}
Experimental setup @ NREL
Experimental results

black start of inverter #1 under 500 W load (making use of almost global stability)

connecting inverter #2 while inverter #1 is regulating the grid under 500 W load

250 W to 750 W load transient with two inverters active

change of setpoint: \( p^* \) of inverter #2 updated from 250 W to 500 W
Detour: **duality & matching** of machines [Arghir & Dörfler,'19]

\[
\begin{align*}
\frac{d\theta}{dt} &= \omega \\
M \frac{d\omega}{dt} &= -D\omega + \tau_m + L_m i_r \begin{bmatrix} -\sin \theta \\ \cos \theta \end{bmatrix}^T \mathbf{i}_s \\
L_s \frac{d\mathbf{i}_s}{dt} &= -R_s \mathbf{i}_s + \mathbf{v}_g - L_m i_r \begin{bmatrix} -\sin \theta \\ \cos \theta \end{bmatrix} \omega
\end{align*}
\]
Detour: **duality & matching** of machines  
[Arghir & Döfler,'19]

\[
\begin{align*}
\frac{d\theta}{dt} &= \omega \\
M \frac{d\omega}{dt} &= -D\omega + \tau_m + Lmi_r \begin{bmatrix} -\sin\theta \\ \cos\theta \end{bmatrix}^\top i_s \\
L_s \frac{di_s}{dt} &= -R_s i_s + v_g - Lmi_r \begin{bmatrix} -\sin\theta \\ \cos\theta \end{bmatrix} \omega \\
C_{dc} \frac{dv_{dc}}{dt} &= -G_{dc}v_{dc} + i_{dc} + m^\top i_f \\
L_f \frac{di_f}{dt} &= -R_f i_f + v_g - m v_{dc}
\end{align*}
\]
Detour: **duality & matching** of machines

[Arghir & Dörfler,'19]

\[
\begin{align*}
\frac{d\theta}{dt} &= \omega \\
M \frac{d\omega}{dt} &= -D\omega + \tau_m + L_m i_r \begin{bmatrix} -\sin \theta \\ \cos \theta \end{bmatrix}^\top i_s \\
L_s \frac{di_s}{dt} &= -R_s i_s + v_g - L_m i_r \begin{bmatrix} -\sin \theta \\ \cos \theta \end{bmatrix} \omega
\end{align*}
\]

1. **modulation in polar coordinates:**

\[
m = m_{\text{ampl}} \begin{bmatrix} -\sin \theta \\ \cos \theta \end{bmatrix} \quad \text{&} \quad \dot{\theta} = m_{\text{freq}}
\]

\[
\begin{align*}
\frac{d\theta}{dt} &= m_{\text{freq}} \\
C_{dc} \frac{dv_{dc}}{dt} &= -C_{dc} v_{dc} + i_{dc} + m_{\text{ampl}} \begin{bmatrix} -\sin \theta \\ \cos \theta \end{bmatrix}^\top i_f \\
L_f \frac{di_f}{dt} &= -R_f i_f + v_g - m_{\text{ampl}} \begin{bmatrix} -\sin \theta \\ \cos \theta \end{bmatrix} v_{dc}
\end{align*}
\]
Detour: **duality & matching** of machines  

[Arghir & Dörfler,'19]

\[ \frac{d\theta}{dt} = \omega \]

\[ M \frac{d\omega}{dt} = -D\omega + \tau_m + L_m i_r \left[ -\sin \theta \right]^\top i_s \]

\[ L_s \frac{di_s}{dt} = -R_s i_s + v_g - L_m i_r \left[ -\sin \theta \right] \omega \]

\[ \frac{d\theta}{dt} = \eta \cdot v_{dc} \]

\[ C_{dc} \frac{dv_{dc}}{dt} = -C_{dc} v_{dc} + i_{dc} + m_{ampl} \left[ -\sin \theta \right]^\top i_f \]

\[ L_f \frac{di_f}{dt} = -R_f i_f + v_g - m_{ampl} \left[ -\sin \theta \right] v_{dc} \]

1. modulation in polar coordinates:

\[ m = m_{ampl} \left[ -\sin \theta \right] \quad \text{&} \quad \dot{\theta} = m_{freq} \]

2. matching: \( m_{freq} = \eta v_{dc} \) with \( \eta = \frac{\omega_{\text{ref}}}{v_{dc,\text{ref}}} \)
Detour: **duality & matching** of machines [Arghir & Dörlfer,'19]

\[
\frac{d\theta}{dt} = \omega \\
M \frac{d\omega}{dt} = -D\omega + \tau_m + L_m i_r \begin{bmatrix} -\sin\theta \\ \cos\theta \end{bmatrix}^\top i_s \\
L_s \frac{di_s}{dt} = -R_s i_s + v_g - L_m i_r \begin{bmatrix} -\sin\theta \\ \cos\theta \end{bmatrix} \omega \\
C_{dc} \frac{dv_{dc}}{dt} = -C_{dc} v_{dc} + i_{dc} + m_{ampl} \begin{bmatrix} -\sin\theta \\ \cos\theta \end{bmatrix}^\top i_f \\
L_f \frac{di_f}{dt} = -R_f i_f + v_g - m_{ampl} \begin{bmatrix} -\sin\theta \\ \cos\theta \end{bmatrix} v_{dc}
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**theory & practice:** **robust** duality \( \omega \sim v_{dc} \)
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► . . . comparison suggests **hybrid VOC + matching control** direction
Comparison of control strategies @AIT

- **all perform well** nominally & under minor disturbances
- **relative resilience**: matching > VOC > droop > virtual synchronous machine

**Fig. 11:** Normalized distribution of the RoCoF $|\dot{\omega}_i|/|\omega_i|$ of the synchronous machine frequency at node 1 for load disturbances $0.75$ p.u. at node 7. For each load disturbance, the converters are able to react faster and more accurately than the SM and the remaining power imbalance affecting the turbine and converter power set-points are set to $0.6$ and $0.75$ p.u. respectively. Note that when the SM at node 1 is disconnected, the interaction of the fast GFC dynamics and slow SM dynamics contributes to the instability shown in Figure 15.

**Fig. 12:** Frequency Stability of Synchronous Machines and Grid-Forming Power Converters

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**Fig. 14:** DC current demand of the converter at node 2 (top) and its DC voltage (bottom) after a $0.75$ p.u. load disturbance (top) and $0.9$ p.u. load disturbance (bottom). The GFCs quickly recover the matching controlled converter $v_{dc}$ when the test system contains one GFC and two SMs, whereas the SM-droop control (VOC) uses GFCs to mimic the synchronizing behavior of the slow synchronous machine and its increased post-event steady-state power injection for several milliseconds. However, due to the comparably slow response, the stability of the system is presented, 3) we explore the behavior of the system when disconnecting the synchronous machine at the base load, is no longer available. Second, the stabilizing mechanism present in SMs and is a widely accepted baseline control (VOC) uses GFCs to mimic the synchronizing behavior of the slow synchronous machine and its increased post-event steady-state power injection for several milliseconds. However, due to the comparably slow response, the stability of the system is presented, 3) we explore the behavior of the system when disconnecting the synchronous machine at the base load, is no longer available. Second, the stabilizing mechanism present in SMs and is a widely accepted baseline

**Fig. 15:** Comparison of control strategies @AIT of Electrical and Computer Engineering, University of Wisconsin-Madison, Control Laboratory, ETH Zürich, Switzerland. D. Groß is with the Department of Electrical and Computer Engineering, University of Wisconsin-Madison.

Funds, and by the European Unions Horizon 2020 research and innovation competence unit of the Austrian Institute for Technology (AIT), ETH Zürich-

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  directions: VOC + matching
Conclusions

Summary

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Main references


→ many other articles on my website (link) under keyword “power electronics control”