Advanced grid-forming control for low-inertia systems

Florian Dörfler

ETH Zürich

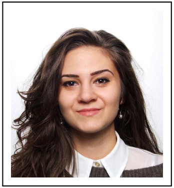
Emerging Topics in Control of Power Systems

Acknowledgements

Marcello Colombino

Ali Tayyebi-Khameneh

Dominic Groß



Irina Subotic

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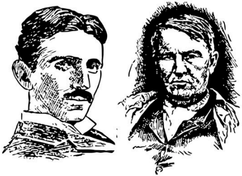
Further: T. Jouini, C. Arghir, A. Anta, B. Johnson, M. Sinha, & S. Dhople

Replacing the power system foundation



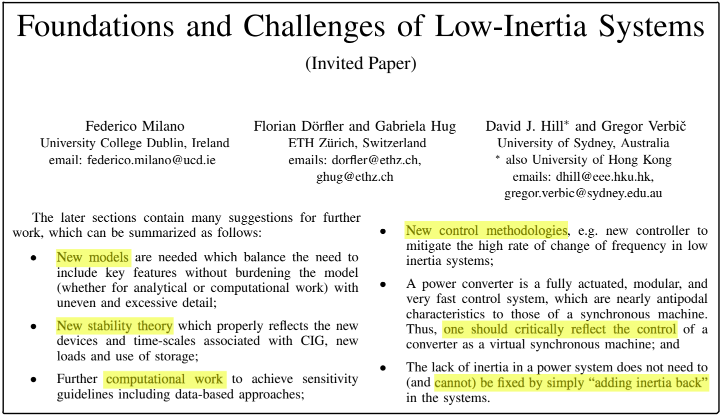
fuel & synchronous machines

- − **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**

Critically re-visit modeling / analysis / control



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.

key unresolved challenge: resilient control of grid-forming power converters

→ industry & academia willing to explore **green-field approach** (see MIGRATE)

Outline

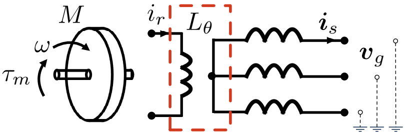
Introduction: Low-Inertia Power Systems

Problem Setup: Modeling and Specifications

State of the Art Grid-Forming Control

Comparison & Discussion

Modeling: synchronous generator



$$\frac{\mathrm{d}\theta}{\mathrm{d}t} = \omega$$

$$M\frac{\mathrm{d}\omega}{\mathrm{d}t} = -D\omega + \tau_m + L_{\mathsf{m}} i_r \left[\begin{smallmatrix} -\sin\theta \\ \cos\theta \end{smallmatrix}\right]^\top \boldsymbol{i}_s$$

$$L_{\mathsf{s}}\frac{\mathrm{d}\boldsymbol{i}_s}{\mathrm{d}t} = -R_s \boldsymbol{i}_s + \boldsymbol{v}_g - L_{\mathsf{m}} i_r \left[\begin{smallmatrix} -\sin\theta \\ \cos\theta \end{smallmatrix}\right] \omega$$

1. ***energy supply*** τ_m from governor
2. mechanical (θ, ω) ***swing dynamics*** of rotor (flywheel) with inertia M
3. $\boldsymbol{i}_s$ ***stator flux dynamics*** (rotor/damper flux dynamics neglected)
4. **electro-mechanical energy conversion** through rotating magnetic field with inductance matrix

$$L_\theta = \begin{bmatrix} L_{\mathsf{s}} & 0 & L_{\mathsf{m}}\cos\theta \\ 0 & L_{\mathsf{s}} & L_{\mathsf{m}}\sin\theta \\ L_{\mathsf{m}}\cos\theta & L_{\mathsf{m}}\sin\theta & L_{\mathsf{r}} \end{bmatrix}$$

Modeling: voltage source converter

1. ***energy supply*** i_{dc} from upstream DC boost converter

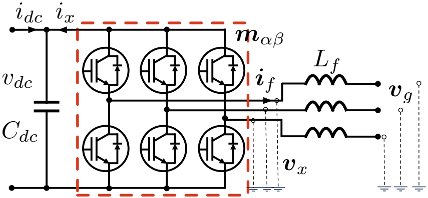
2. ***DC link dynamics*** v_{dc} with capacitance C_{dc}

3. $\boldsymbol{i}_f$ ***AC filter dynamics*** (sometimes also LC or LCL)

4. **power electronics modulation**

$$i_x = -\boldsymbol{m}^\top \boldsymbol{i}_f \quad \text{and} \quad \boldsymbol{v}_x = \boldsymbol{m} v_{\text{dc}} \, ,$$

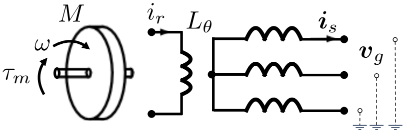
with averaged & normalized duty cycle ratios $\boldsymbol{m} \in [-\frac{1}{2}, \frac{1}{2}] \times [-\frac{1}{2}, \frac{1}{2}]$

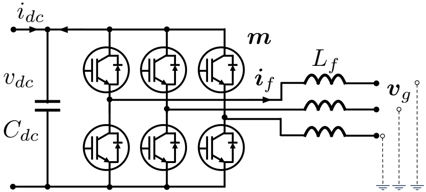


$$C_{\text{dc}} \frac{\mathrm{d}v_{\text{dc}}}{\mathrm{d}t} = -G_{\text{dc}} v_{\text{dc}} + i_{\text{dc}} + \boldsymbol{m}^\top \boldsymbol{i}_f$$

$$L_f \frac{\mathrm{d}\boldsymbol{i}_f}{\mathrm{d}t} = -R_f \boldsymbol{i}_f + \boldsymbol{v}_g - \boldsymbol{m} \, v_{\text{dc}}$$

Comparison: conversion mechanisms





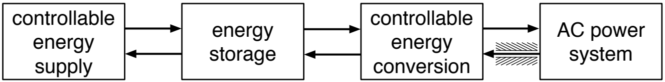
$$\frac{\mathrm{d}\theta}{\mathrm{d}t} = \omega$$

$$M\frac{\mathrm{d}\omega}{\mathrm{d}t} = -D\omega + \tau_m + L_\mathrm{m} i_r \begin{bmatrix} -\sin\theta \\ \cos\theta \end{bmatrix}^\top \boldsymbol{i}_s$$

$$L_\mathrm{s}\frac{\mathrm{d}\boldsymbol{i}_s}{\mathrm{d}t} = -R_s\boldsymbol{i}_s + \boldsymbol{v}_g - L_\mathrm{m} i_r \begin{bmatrix} -\sin\theta \\ \cos\theta \end{bmatrix}\omega$$

$$C_\mathrm{dc}\frac{\mathrm{d}v_\mathrm{dc}}{\mathrm{d}t} = -G_\mathrm{dc}v_\mathrm{dc} + i_\mathrm{dc} + \boldsymbol{m}^\top \boldsymbol{i}_f$$

$$L_f\frac{\mathrm{d}\boldsymbol{i}_f}{\mathrm{d}t} = -R_f\boldsymbol{i}_f + \boldsymbol{v}_g - \boldsymbol{m}\, v_\mathrm{dc}$$


controllable energy supply

energy storage

controllable energy conversion

AC power system

τ_m (slow)
vs.
i_dc (fast)

M (large)
vs.
C_dc (small)

L_θ (physical)
vs.
$\boldsymbol{m}$ (control)

resilient
vs.
fragile
(over-currents)

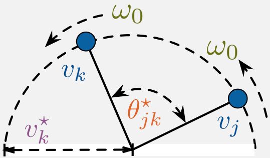
physical & robust
vs.
controlled & agile
signal / energy transformer

Objectives for grid-forming converter control ($\alpha\beta$ frame)

stationary control objectives

- synchronous frequency

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



- voltage amplitude $\|v_k\| = v_k^\star$
- active & reactive power injections

$$v_k^\top i_{f,k} = p_k^\star \;, \quad v_k^\top \left[\begin{smallmatrix} 0 & -1 \\ +1 & 0 \end{smallmatrix}\right] i_{f,k} = q_k^\star$$

$\overset{\text{unique}}{\underset{\text{conversion}}{\Longleftrightarrow}}$ relative voltage angles

$$v_k = \begin{bmatrix} \cos(\theta^\star_{jk}) & -\sin(\theta^\star_{jk}) \\ \sin(\theta^\star_{jk}) & \cos(\theta^\star_{jk}) \end{bmatrix} v_j$$

dynamic control objectives

- droop at perturbed operation: $\omega - \omega_0 = k \cdot (p - p^\star)$ with specified power/frequency sensitivity $k = \frac{\partial p}{\partial \omega}$ droop (similar for $\|v\|$ and q)
- disturbance (fault) rejection: passively via physics (inertia) or via control
- grid-forming: intrinsic synchronization rather than tracking of exogenous ω_0

Naive baseline solution: emulation of virtual inertia

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storage
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provide

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Improvement of Transient Response in Microgrids Using Virtual Inertia

Nimish Soni, *Student Member, IEEE*, Suryanarayana Doolla, *Member, IEEE*, and Mukul C. Chandorkar, *Member, IEEE*

IEEE TRANSACTIONS ON POWER SYSTEMS, VOL. 28, NO. 2, MAY 2013 1373

Implementing Virtual Inertia in DFIG-Based Wind Power Generation

mmadreza Fakhari Moghaddam Arani, *Student Member, IEEE*, and Ehab F. El-Saadany, *Senior Member, IEEE*

Virtual synchronous generators: A survey and new perspectives

Hassan Bevrani^{a,b,*}, Toshifumi Ise^{b}, Yushi Miura^{b}

[a] *Dept. of Electrical and Computer Eng., University of Kurdistan, PO Box 416, Sanandaj, Iran*
[b] *Dept. of Electrical, Electronic and Information Eng., Osaka University, Osaka, Japan*

Dynamic Frequency Control Support: a Virtual Inertia Provided by Distributed Energy Storage to Isolated Power Systems

iauthier Delille, *Member, IEEE*, Bruno François, *Senior Member, IEEE*, and Gilles Malarange

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IEEE TRANSACTIONS ON POWER SYSTEMS, VOL. 28, NO. 2, MAY 2013

Inertia Emulation Control Strategy for VSC-HVDC Transmission Systems

Jiebei Zhu, Campbell D. Booth, Grain P. Adam, Andrew J. Roscoe, and Chris G. Bright

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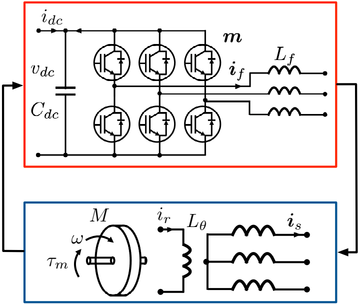
Grid Tied Converter with Virtual Kinetic Storage

M.P.N van Wesenbeeck[1], S.W.H. de Haan[1], *Senior member, IEEE*, P. Varela[2] and K. Visscher[3],

Virtual synchronous machine ≡ flywheel emulation



- ***reference model*** for converter voltage loop : detailed model of synchronous generator + controls (of order 3,. . . ,12)

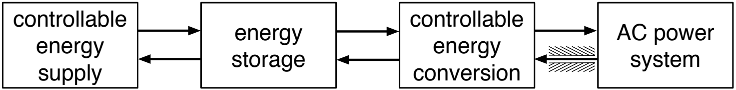
→ most commonly **accepted solution** in **industry** (¿ backward compatibility ?)

- robust ***implementation needs tricks***: low-pass filters for dissipation, virtual impedances for saturation, limiters,. . .

→ performs well in small-signal regime but **performs very poorly post-fault**

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

→ **poor fit**: converter ≠ flywheel
very different actuation & energy storage



controllable energy supply | energy storage | controllable energy conversion | AC power system

slow vs. fast | large vs. small | physics vs. control | resilient vs. fragile

Droop as simplest reference model

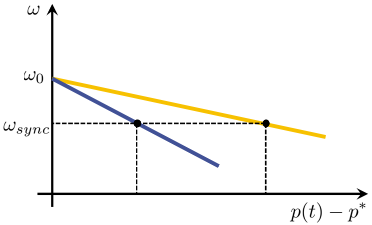
[Chandorkar, Divan, Adapa, ’93]

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

$$\omega - \omega_0 \;\propto\; p - p^\star$$

- ***voltage control*** via $q - \|v\|$ droop control:

$$\tfrac{d}{dt}\|v\| = -c_1(\|v\| - v^\star) - c_2(q - q^\star)$$



- ***reference*** are generator controls

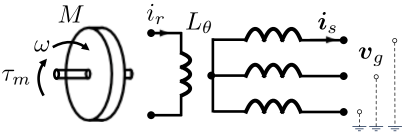
→ direct control of (p,ω) and $(q,\|v\|)$ **assuming they are independent** (approx. true only near steady state)

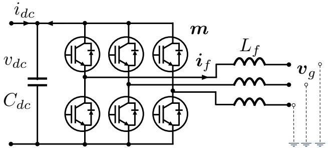
→ requires **tricks in implementation** : similar to virtual synchronous machine

→ **good small-signal but poor large signal behavior** (rather narrow region of attraction)

→ main reason for poor performance: **two linear SISO loops for MIMO nonlinear system** (SISO & linear only near steady state)

Duality & matching of synchronous machines [Arghir & Dörfler,'19]





$$\frac{\mathrm{d}\theta}{\mathrm{d}t} = \omega$$

$$M\frac{\mathrm{d}\omega}{\mathrm{d}t} = -D\omega + \tau_m + L_{\mathrm{m}} i_r \begin{bmatrix} -\sin\theta \\ \cos\theta \end{bmatrix}^\top \boldsymbol{i}_s$$

$$L_{\mathrm{s}}\frac{\mathrm{d}\boldsymbol{i}_s}{\mathrm{d}t} = -R_s \boldsymbol{i}_s + \boldsymbol{v}_g - L_{\mathrm{m}} i_r \begin{bmatrix} -\sin\theta \\ \cos\theta \end{bmatrix} \omega$$

$$\frac{\mathrm{d}\theta}{\mathrm{d}t} = \eta \cdot v_{\mathrm{dc}}$$

$$C_{\mathrm{dc}}\frac{\mathrm{d}v_{\mathrm{dc}}}{\mathrm{d}t} = -G_{\mathrm{dc}} v_{\mathrm{dc}} + i_{\mathrm{dc}} + m_{\mathrm{ampl}} \begin{bmatrix} -\sin\theta \\ \cos\theta \end{bmatrix}^\top \boldsymbol{i}_f$$

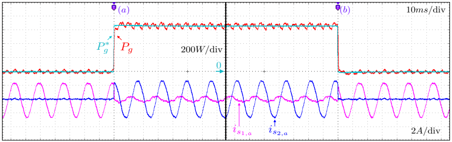
$$L_f\frac{\mathrm{d}\boldsymbol{i}_f}{\mathrm{d}t} = -R_f \boldsymbol{i}_f + \boldsymbol{v}_g - m_{\mathrm{ampl}} \begin{bmatrix} -\sin\theta \\ \cos\theta \end{bmatrix} v_{\mathrm{dc}}$$

1. modulation in polar coordinates:

$$\boldsymbol{m} = m_{\mathrm{ampl}} \begin{bmatrix} -\sin\theta \\ \cos\theta \end{bmatrix} \quad \& \quad \dot{\theta} = m_{\mathrm{freq}}$$

2. ***matching***: $m_{\mathrm{freq}} = \eta v_{\mathrm{dc}}$ with $\eta = \frac{\omega_{\mathrm{ref}}}{v_{\mathrm{dc,ref}}}$

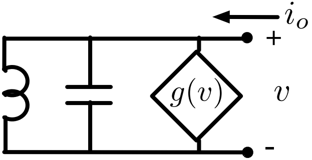
→ ***duality***: $C_{\mathrm{dc}} \sim M$ is equivalent inertia

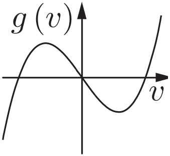


theory & practice: ***robust*** duality $\omega \sim v_{\mathrm{dc}}$

Original **V**irtual **O**scillator **C**ontrol (VOC)

nonlinear & open limit cycle oscillator as reference model for converter voltage loop





- simplified model amenable to theoretic analysis

  [J. Aracil & F. Gordillo, ’02], [Torres, Hespanha, Moehlis, ’11], [Johnson, Dhople, Krein, ’13], [Dhople, Johnson, Dörfler, ’14]

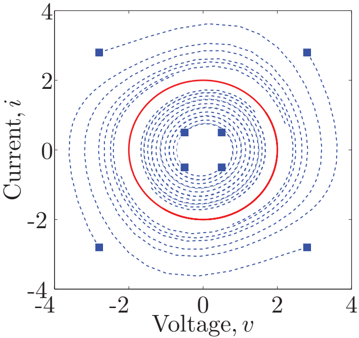
→ ***almost global synchronization*** & ***local droop***

- in practice proven to be ***robust mechanism*** with performance superior to droop & others

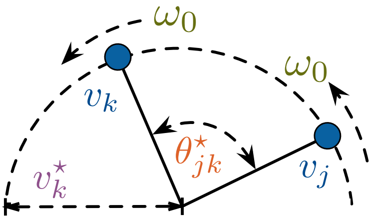
→ **problem** : cannot be controlled(?) to meet specifications on amplitude & power injections

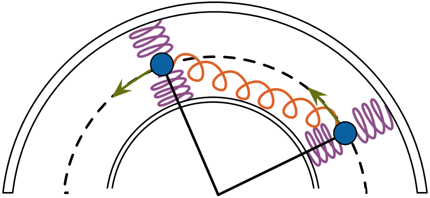
→ ***dispatchable*** virtual oscillator control

[Colombino, Groß, Brouillon, & Dörfler, ’17, ’18,’19], [Subotic, Gross, Colombino, & Dörfler,’19]



Colorful idea: closed-loop target dynamics





$$\frac{d}{dt}\boldsymbol{v_k} = \underbrace{\begin{bmatrix} 0 & -\omega_0 \\ \omega_0 & 0 \end{bmatrix} \boldsymbol{v_k}}_{\text{rotation at } \omega} + c_2 \cdot \underbrace{\left(\|v_k\|^{\star 2} - \|\boldsymbol{v}_k\|^2 \right) \boldsymbol{v}_k}_{\text{amplitude regulation to } v^\star_k}$$

$$+ \; c_1 \cdot \underbrace{\sum_{j=1}^{n} w_{jk} \left(\boldsymbol{v}_j - \begin{bmatrix} \cos(\theta^\star_{jk}) & -\sin(\theta^\star_{jk}) \\ \sin(\theta^\star_{jk}) & \cos(\theta^\star_{jk}) \end{bmatrix} \boldsymbol{v}_k \right)}_{\text{synchronization to desired relative angles } \theta^\star_{jk}}$$

Properties of virtual oscillator control

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

$$\frac{d}{dt}v_k = \underbrace{\begin{bmatrix}0 & -\omega_0\\ \omega_0 & 0\end{bmatrix}}_{\text{rotation at }\omega_0} v_k + c_1\cdot\underbrace{\left(\frac{1}{v_k^{\star 2}}\begin{bmatrix} q_k^\star & p_k^\star \\ -p_k^\star & q_k^\star\end{bmatrix} v_k - i_{f,k}\right)}_{\text{synchronization through grid current}} + c_2\cdot\underbrace{\left(v_k^{\star 2} - \|v_k\|^2\right) v_k}_{\text{local amplitude regulation}}$$

2. connection to ***droop control*** seen in polar coordinates (though multivariable)

$$\frac{d}{dt}\theta_k = \omega_0 + c_1\left(\frac{p_k^\star}{v_k^{\star 2}} - \frac{p_k}{\|v_k\|^2}\right) \underset{\|v_k\|\approx 1}{\approx} \omega_0 + c_1\left(p_k^\star - p_k\right) \quad (p-\omega \text{ droop})$$

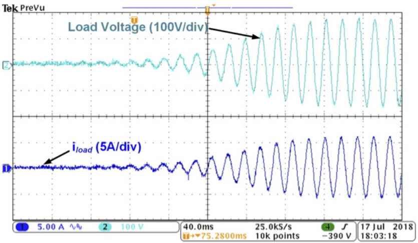
$$\frac{d}{dt}\|v_k\| \underset{\|v_k\|\approx 1}{\approx} c_1\left(q_k^\star - q_k\right) + c_2\left(v_k^\star - \|v_k\|\right) \qquad (q-\|v\| \text{ droop})$$

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

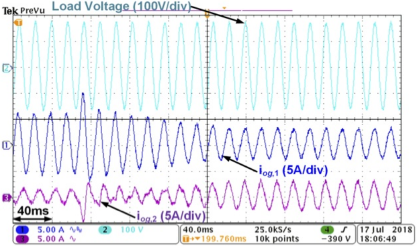
- **power transfer** “small” compared to **network connectivity**
- **amplitude control** “slower” than **synchronization control**

Experimental results

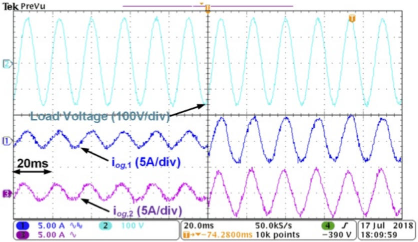
[Seo, Subotic, Johnson, Colombino, Groß, & Dörfler, ’19]



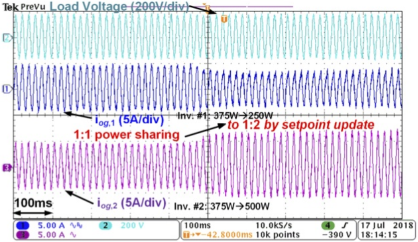
black start of inverter #1 under 500 W load (making use of almost global stability)



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

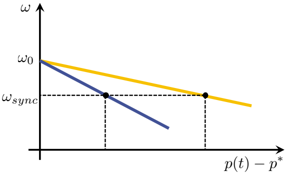


250 W to 750 W load transient with two inverters active



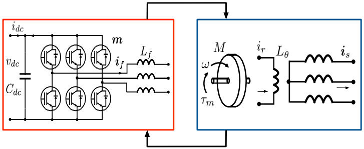
change of setpoint: $p^\star$ of inverter #2 updated from 250 W to 500 W

High-level comparison of grid-forming control



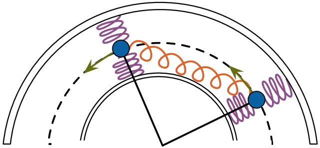
droop control

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



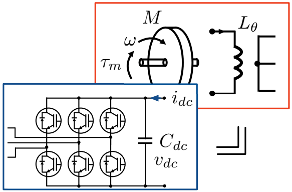
synchronous machine emulation

+ backward compatible in nominal case
− not resilient under large disturbances



virtual oscillator control

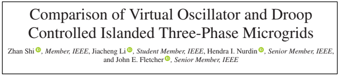
+ excellent large-signal behavior + local droop



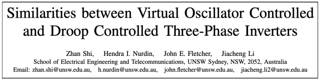
matching control & duality

+ simple & robust

Detailed comparison(s) of control strategies


Comparison of Virtual Oscillator and Droop Controlled Islanded Three-Phase Microgrids

Zhan Shi, *Member, IEEE*, Jiacheng Li, *Student Member, IEEE*, Hendra I. Nurdin, *Senior Member, IEEE*, and John E. Fletcher, *Senior Member, IEEE*


Similarities between Virtual Oscillator Controlled and Droop Controlled Three-Phase Inverters

Zhan Shi, Hendra I. Nurdin, John E. Fletcher, Jiacheng Li
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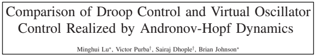
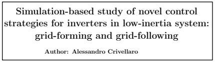
Frequency Stability of Synchronous Machines and Grid-Forming Power Converters

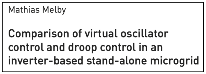
Ali Tayyebi, Dominic Groß, Adolfo Anta, Friederich Kupzog and Florian Dörfler, *Member, IEEE*


Comparison of Droop Control and Virtual Oscillator Control Realized by Andronov-Hopf Dynamics

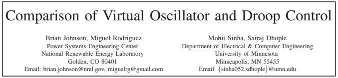
Minghui Lu*, Victor Purba†, Sairaj Dhople†, Brian Johnson*


Simulation-based study of novel control strategies for inverters in low-inertia system: grid-forming and grid-following

Author: Alessandro Crivellaro


Mathias Melby

Comparison of virtual oscillator control and droop control in an inverter-based stand-alone microgrid


Comparison of Virtual Oscillator and Droop Control

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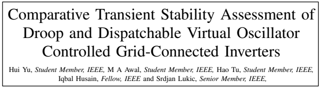
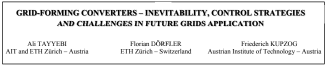

Comparative Transient Stability Assessment of Droop and Dispatchable Virtual Oscillator Controlled Grid-Connected Inverters

Hui Yu, *Student Member, IEEE,* M A Awal, *Student Member, IEEE,* Hao Tu, *Student Member, IEEE,* Iqbal Husain, *Fellow, IEEE* and Srdjan Lukic, *Senior Member, IEEE,*


GRID-FORMING CONVERTERS – INEVITABILITY, CONTROL STRATEGIES *AND CHALLENGES IN FUTURE GRIDS APPLICATION*

Ali TAYYEBI
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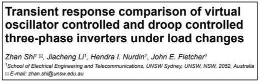
Florian DÖRFLER
ETH Zürich – Switzerland

Friederich KUPZOG
Austrian Institute of Technology – Austria


Transient response comparison of virtual oscillator controlled and droop controlled three-phase inverters under load changes

Zhan Shi[1] ✉, Jiacheng Li[1], Hendra I. Nurdin[1], John E. Fletcher[1]
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Grid-Forming Converters control based on DC voltage feedback

Yuan Gao[a], Hai-Peng Ren[a], Jie Li[a]

- ***identical steady-state & similar small-signal behavior*** (after tuning)
- ***virtual synchronous machine*** has poor transients (converter $\neq$ flywheel)
- **VOC has best large-signal behavior**: stability, post-fault-response, …
- **matching control** $\omega \sim v_{\mathrm{dc}}$ **is most robust** though with slow AC dynamics
- …comparison suggests ***hybrid VOC + matching control*** direction

Hybrid angle control = matching + oscillator control

hybrid angle control dynamics

$$\dot{\theta} = \omega_0 + c_1 \cdot \underbrace{\left(v_{\mathrm{dc}} - v_{\mathrm{dc}}^{\star}\right)}_{\text{matching control term}} + \underbrace{c_2 \cdot \sin\left(\frac{\theta - \theta_{\mathrm{grid}} - \theta^{\star}}{2}\right)}_{1/2 \text{ synchronizing oscillator term}}$$

implementation aspects

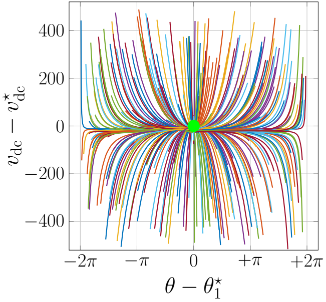
- **tuning** gains: c_1 & c_2 (robustness & performance)
- error signals ← **voltage & current measurements**
- θ either **voltage reference** or **modulation angle**

a few selected ***theoretical certificates***

- **almost global stability** for sufficiently large c_2/c_1
- **compatibility**: local droop behavior & stability preserved under dc source or ac grid dynamics
- active **current limitation** (pulling down modulation magnitude) with guaranteed closed-loop stability

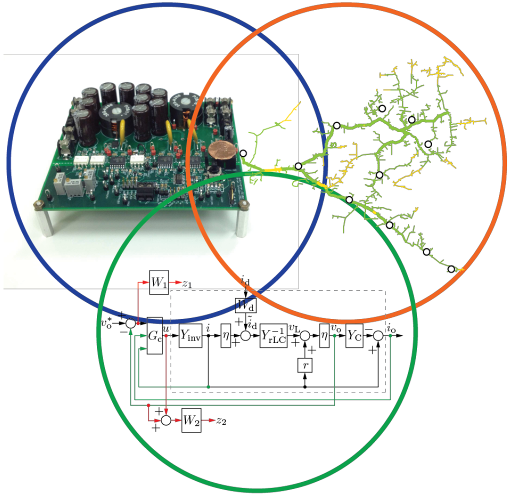
Hybrid Angle Control and Almost Global Stability
of Grid-Forming Power Converters

Ali Tayyebi, Adolfo Anta, and Florian Dörfler



theory: **best grid-forming control** (!) → ongoing work: practice

Exciting research bridging communities



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→ today's references on my website (`link`) under the keyword "power electronics control"