Grid-forming converters

Recreating electromechanical synchronous generators through power electronics

LISTalks on Energy Transition: On the dominant role of power electronics in modern power systems

Pedro Rodriguez
February 23rd 2022

LUXEMBOURG
INSTITUTE
OF SCIENCE
AND TECHNOLOGY

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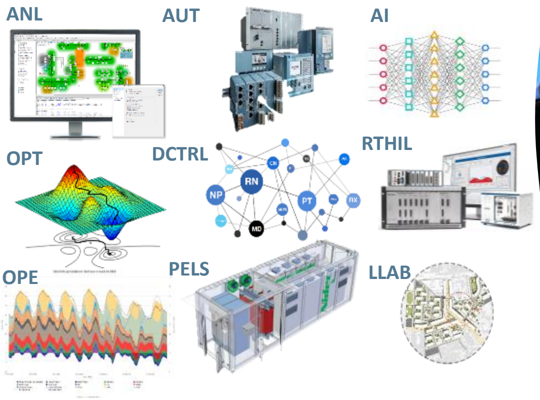
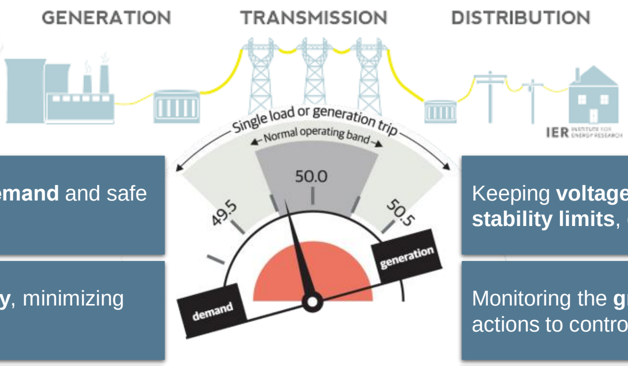
LIST-ICES

The Intelligent Clean Energy Systems (**ICES**) develops innovative market-oriented solutions and services for distributed energy systems of the future.



The ac electrical product: voltage amplitude and frequency

System Operator



Objectives

Covering consumers' demand and safe operation optimizing cost

Ensure **security of supply**, minimizing the probability of failures

Supply electrical energy to consumers, fulfilling **voltage quality standards**

Challenges

Keeping **voltage parameters within stability limits**, even under disturbances

Monitoring the **grid state** and making actions to control the electrical grid

Dealing with **system faults**, conducting fast detection and mitigation

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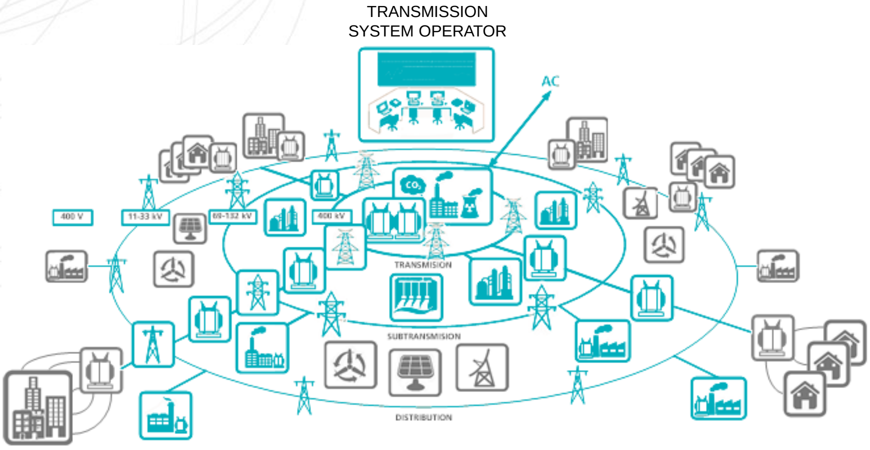
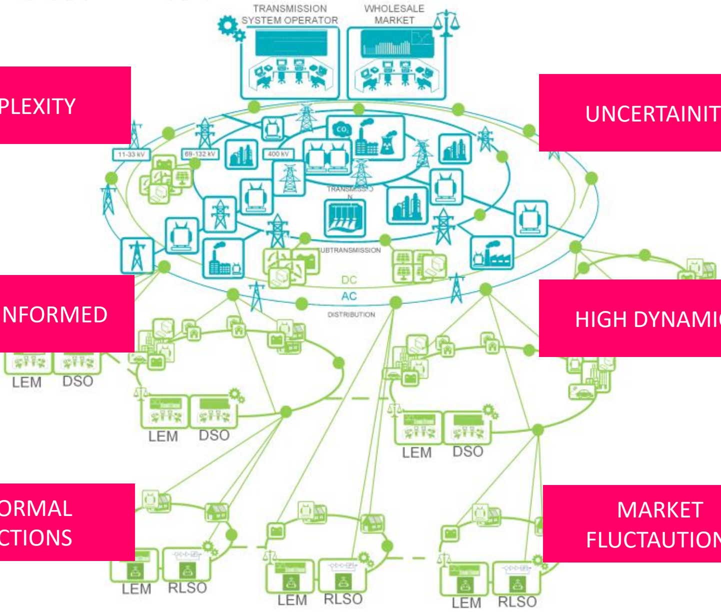
Traditional scenario



- Conventional infrastructures
- Centralized control
- Unidirectional power flow
- Carbonized generation
- Increasing RES penetration (variability)
- Conventional electricity markets
- Passive consumers
- Increasing electric demand
- Grid congestion, fluctuation, weakness..
- Lack of flexibility
- New regulations on user-centric models
- New business models yet for coming

Future scenario



COMPLEXITY

UNCERTAINITY

HYPER-INFORMED

HIGH DYNAMICS

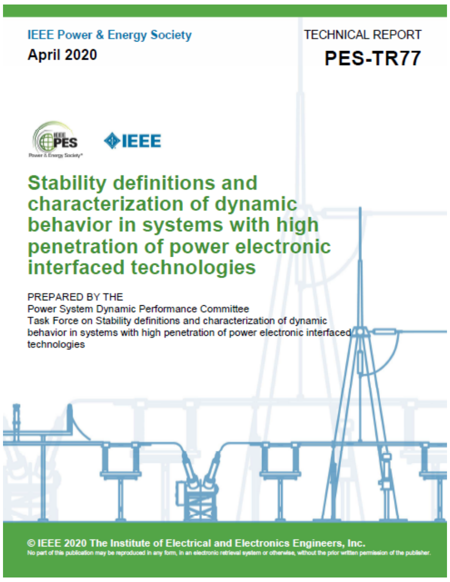
ABNORMAL REACTIONS

MARKET FLUCTUATIONS

- Renewable generation
- Transmission as a framework supporting distributed energy
- Decentralized control
- Energy storage
- Electrical vehicles
- Active prosumers and energy communities
- Local energy markets and services
- Multi-terminal dc networks at all voltage levels
- Intelligence spread all over the system
- New requirements: robustness and resiliency

System stability

- Dynamic behaviour of power systems **was** predominantly determined by the dynamic performance of synchronous generators and their controls as well as the dynamic performance of the loads.
- The stability issues arise due to **interactions between power converter (PC) controls, reduction in total power system inertia, and limited contribution to short circuit currents from PC during faults**
- **Key attributes** to be considered to evaluate the impact of PC:
  - PC can provide limited short-circuit current contribution
  - The PLL and inner-current control loop play a major role in the dynamic recovery after a fault
  - The overall dynamic performance of CIGs is largely determined by the dynamic characteristics of the PLL



IEEE Power & Energy Society
April 2020

TECHNICAL REPORT
PES-TR77

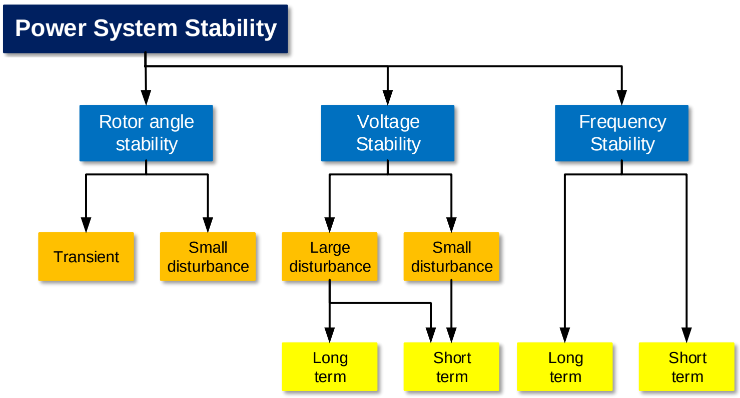
Stability definitions and characterization of dynamic behavior in systems with high penetration of power electronic interfaced technologies

PREPARED BY THE
Power System Dynamic Performance Committee
Task Force on Stability definitions and characterization of dynamic behavior in systems with high penetration of power electronic interfaced technologies

System stability

Formal definition

> *"Power system stability is the ability of an electric power system, for a given initial operating condition, **to regain a state of operating equilibrium after being subjected to a physical disturbance**, with most system variables bounded so that practically the entire system remains intact."*



Power System Stability

- Rotor angle stability
  - Transient
  - Small disturbance
- Voltage Stability
  - Large disturbance
    - Long term
    - Short term
  - Small disturbance
    - Short term
- Frequency Stability
  - Long term
  - Short term

System stability

Formal definition

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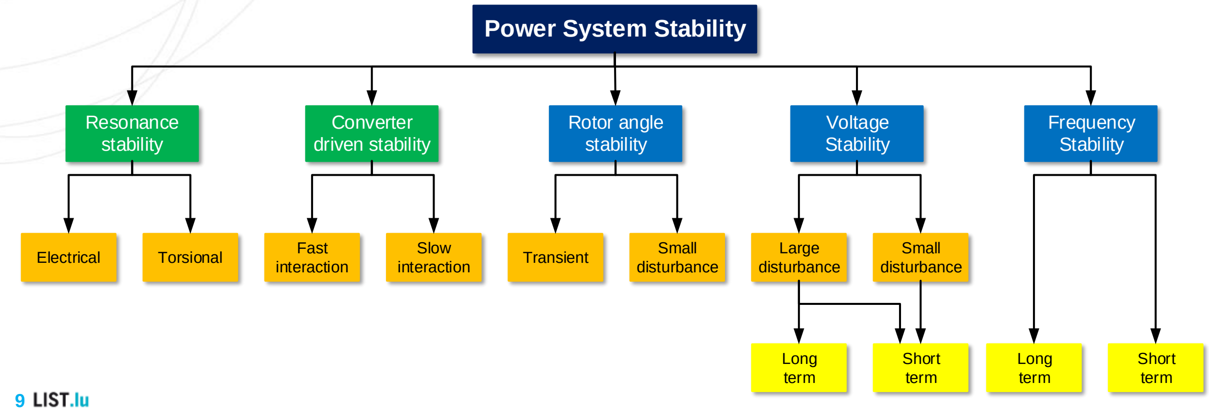


Power System Stability

Resonance stability
Converter driven stability
Rotor angle stability
Voltage Stability
Frequency Stability

Electrical
Torsional
Fast interaction
Slow interaction
Transient
Small disturbance
Large disturbance
Small disturbance

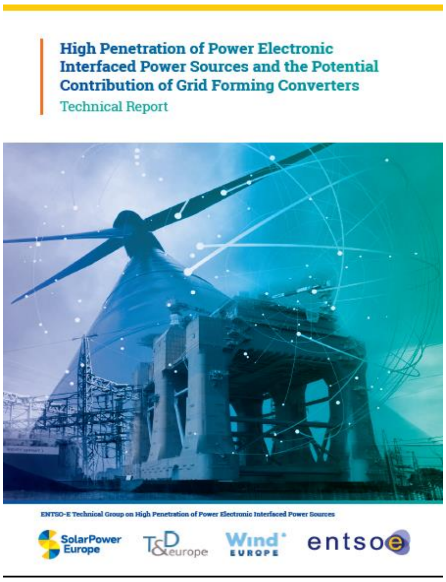
Long term
Short term
Long term
Short term

Grid forming (GFM) power converters

Class 3 PPMs **shall be capable of supporting the operation of the ac power system under normal, alerted, emergency, blackout and restoration states without having to rely on services from synchronous generators**. This shall include the capabilities for stable operation for the extreme operating case of supplying the complete demand from **100% converter based power sources**. The capabilities expected are limited by boundaries of defined capabilities (such as short term current carrying capacity and stored energy).

Key capabilities of grid froing converters:

- Creating system voltage
- Contributing to fault level
- Sink for harmonics
- Sink for unbalance
- Contribution to inertia
- System survival to allow effective operation of Low Frequency Demand Disconnection (LFDD)
- Preventing adverse control interactions



High Penetration of Power Electronic Interfaced Power Sources and the Potential Contribution of Grid Forming Converters
Technical Report

ENTSO-E Technical Group on High Penetration of Power Electronic Interfaced Power Sources

Grid forming (GFM) power converters

Here, we use the term grid-forming as an umbrella for **any inverter controller that regulates instantaneous terminal voltages and can coexist with other grid-following and grid-forming inverters and synchronous generation on the same system**. In principle, grid-forming inverters should allow for the realization of scalable and decentralized AC power systems where system voltages and frequency are regulated by the collective interactions of the grid-forming units themselves. Our use of the term grid-forming also excludes single-inverter stand-alone systems or multi-inverter systems that require communications to operate.

Grid-Forming Control

- Assumes it has responsibility to form and maintain healthy grid
- Control of voltage magnitude and frequency/phase
- Slight coupling between P and Q
- It may use PLL control to switch between modes
- Can black-start a power system
- *Can theoretically operate* at 100% power electronics penetration; can coexist with grid-following
- Not standardized, inadequate operational experience at a systems perspective

Research Roadmap on
Grid-Forming Inverters

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With editing and support from Hariharan Krishnaswami[6],
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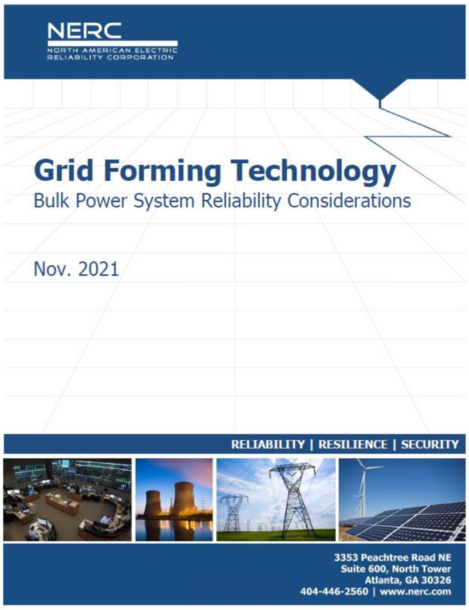
Grid forming (GFM) power converters

Grid Forming Control for BPS-Connected Inverter-Based Resources: controls with the primary objective to **maintain an internal voltage phasor that is constant or nearly constant in the sub-transient to transient time frame**.

The voltage phasor must be controlled to maintain synchronism with other devices in the grid and must also regulate active and reactive power appropriately to support the grid.

GFM control are recommended to **provide robust dynamic support to the grid including** (but not limited to):

- Operation in low system strength condition
- Grid frequency and voltage stabilization
- Small signal stability damping to maintain power system stability
- Re-synchronization capability to restore and reconnect to the grid
- Fault ride through for large grid disturbance events with adequate fault current contribution as required by protection systems (if hardware limits allow)
- System restoration and blackstart capability (for some GFM inverters)



NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

Grid Forming Technology
Bulk Power System Reliability Considerations

Nov. 2021

RELIABILITY | RESILIENCE | SECURITY

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Suite 600, North Tower
Atlanta, GA 30326
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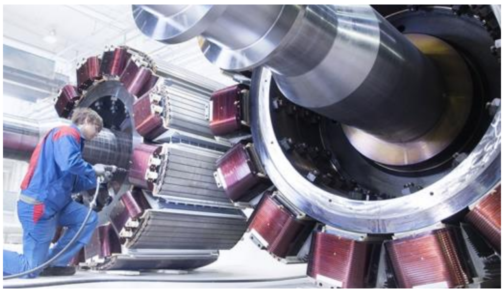
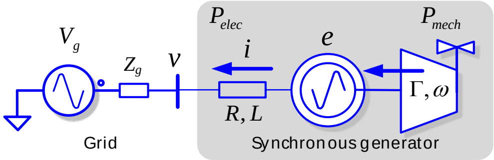
Synchronous generator

- Only rotates in one direction
- It has only one rotor, with a single speed
- Its natural damping is almost zero
- Its inertia has a single value
- Its electromechanical response is very slow
- Its impedance has a single value
- Its output impedance is highly inductive
- Its physical parameters are invariant





Electromagnetic interaction →

$$v(s) = e(s) - i(s)(R + Ls)$$

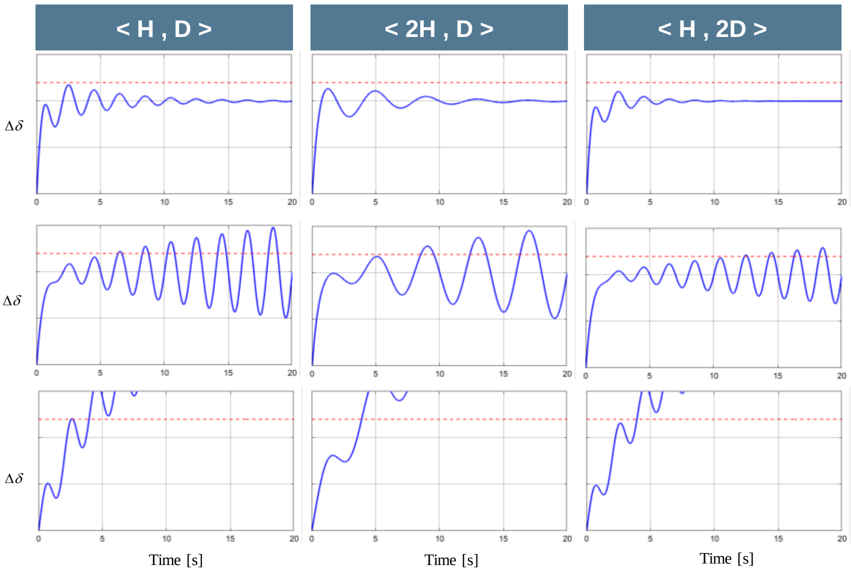
Electromechanical interaction →

$$P_m - P_e = \left(\frac{2H}{\omega_S}s + D\right)\omega$$

$$\omega = s\theta$$

Damping torque and synchronization torque

- Stable response
- Insufficient damping torque
- Insufficient synchronization torque



Electrical grid interaction

- A synchronous generator naturally injects reactive power to the grid in case of the grid voltage drops.

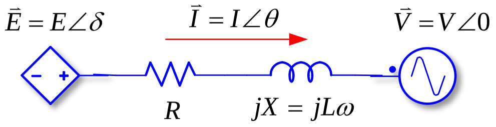
$$E_d = E\cos\delta \quad ; \quad E_q = E\sin\delta$$
$$I_d = I\cos\theta \quad ; \quad I_q = I\sin\theta$$

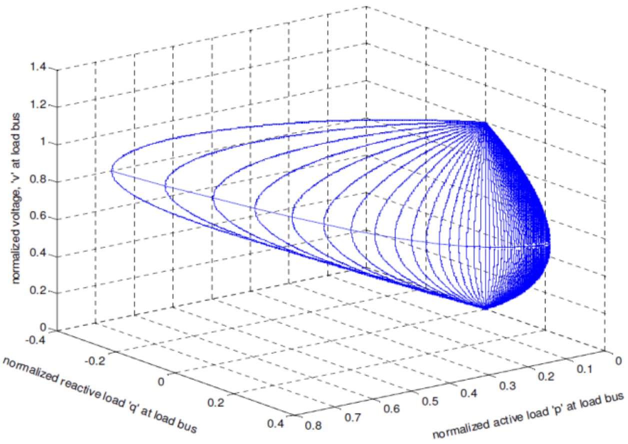
$$\begin{pmatrix}P\\ Q\end{pmatrix} = \frac{V}{R^2+X^2}\begin{pmatrix}R & X\\ -X & R\end{pmatrix}\begin{pmatrix}E_d - V\\ E_q\end{pmatrix}$$

- Maximum limit for transferring active and reactive power. Considering a pure inductive line and normalizing:

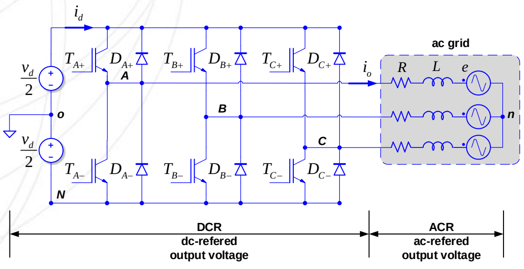
$$R = 0\,;\ v = \frac{V}{E}\,; p = \frac{P\cdot X}{E^2}\,; q = \frac{Q\cdot X}{E^2} I_d$$

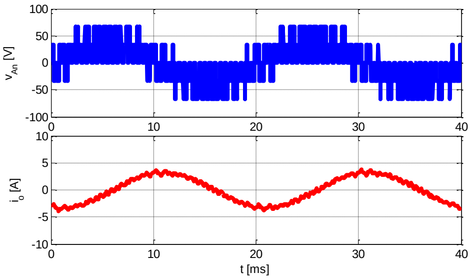
$$v = \sqrt{\frac{1}{2} - q \pm \sqrt{\frac{1}{4} - p^2 - q}}$$



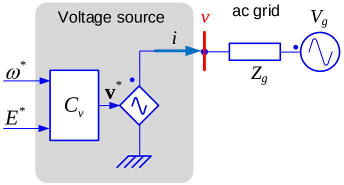


Voltage Source Converter (VSC)

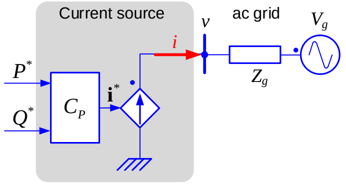




Voltage controlled VSC

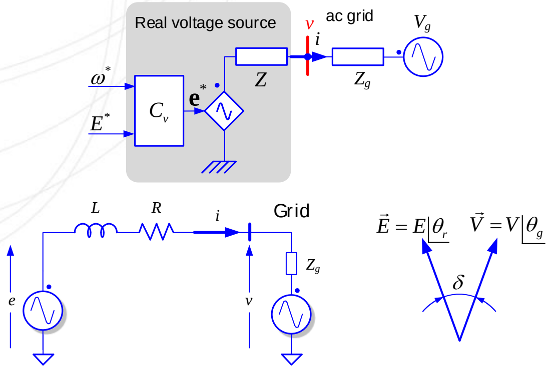


Current controlled VSC



Voltage Source Converter (VSC)

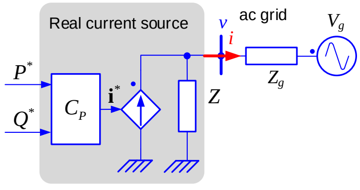
Real voltage controlled VSC



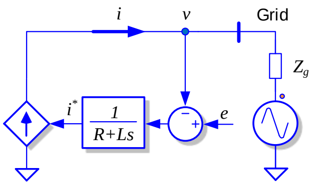
$$v(t) = e(t) - Ri(t) - L\frac{di(t)}{dt}$$

$$v(s) = e(s) - i(s)(R + Ls)$$

Real current controlled VSC

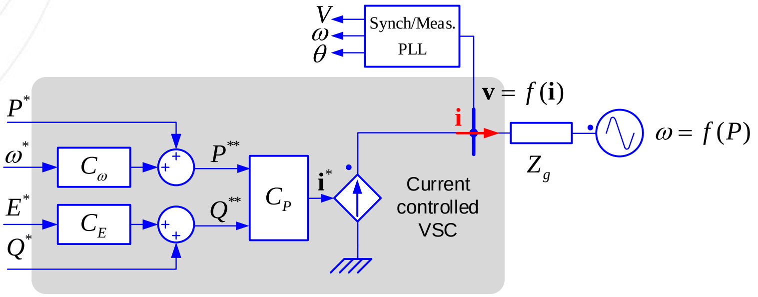


$$i(s) = \frac{1}{R + sL}\left(e(s) - v(s)\right)$$



Grid-following (GFL) power converter

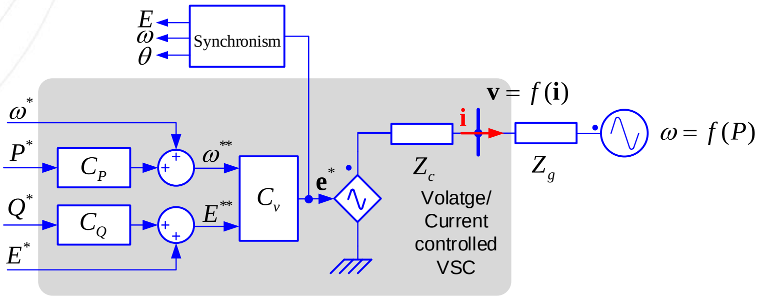
Grid voltage-based synchronization mechanism (PLL, FLL, Fourier)



A GFL power converter is a system with ‘no-memory’ about the power system state. It just observes the PCC state (frequency/voltage/phase-angle) with some delay and reacts to it to achieve a given set-point in terms of power, current or voltage at the PCC

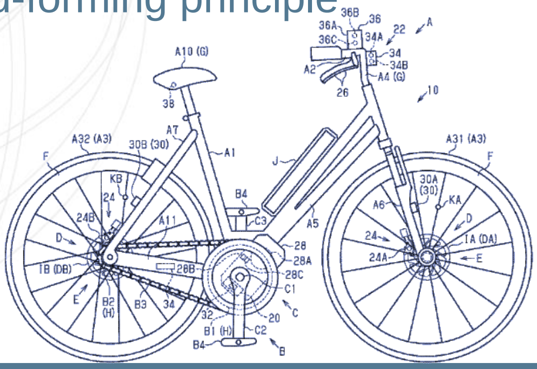
Grid-forming (GFM) power converter

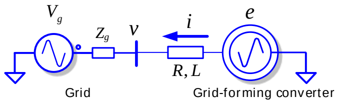
Power balance-based synchronization mechanism (motion equation, PI, lead-lag)

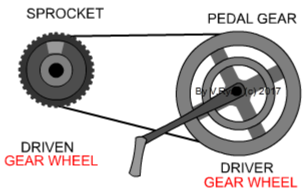


A GFM power converter, thank to its inertia emulation, memorizes the power converter state (internal voltage/phase-angle) and reacts to the grid contingences to maintain its energy state unchanged, eventually evolving toward a new energy state coherent with the new power system state (power-based synchronization).

Grid-forming principle



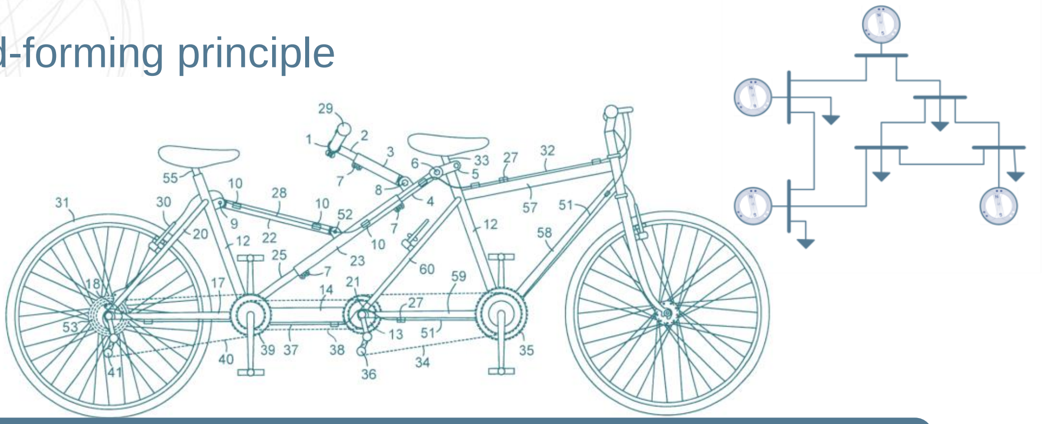




Riding a bike is not a matter of stepping on the pedals, but simply of pedalling.

A grid forming converter should not follow the sinusoidal voltages at the PCC, but just to behave as a synchronous systems

Grid-forming principle

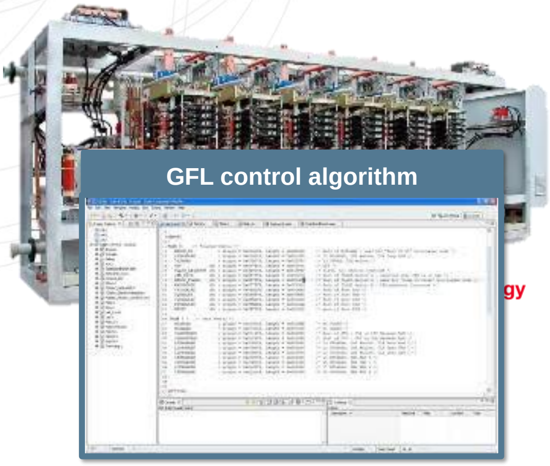


Even tough you might ride a tandem bike alone; you are part of a team.

A grid forming converter should ‘synchronously feel’ the grid ,and respond in solidarity according to its capacity and parameters

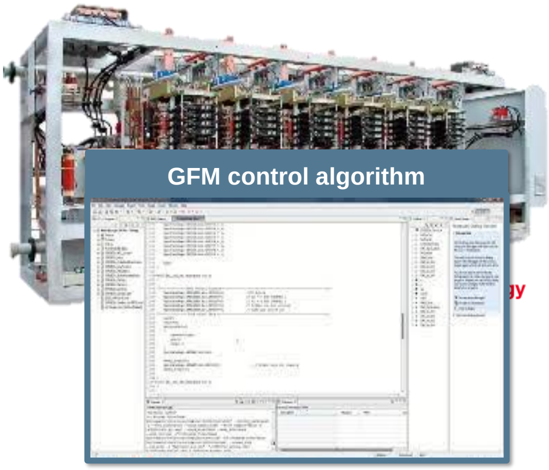
Implementing GFL and GFM power converters

Grid following (GFL) power converter



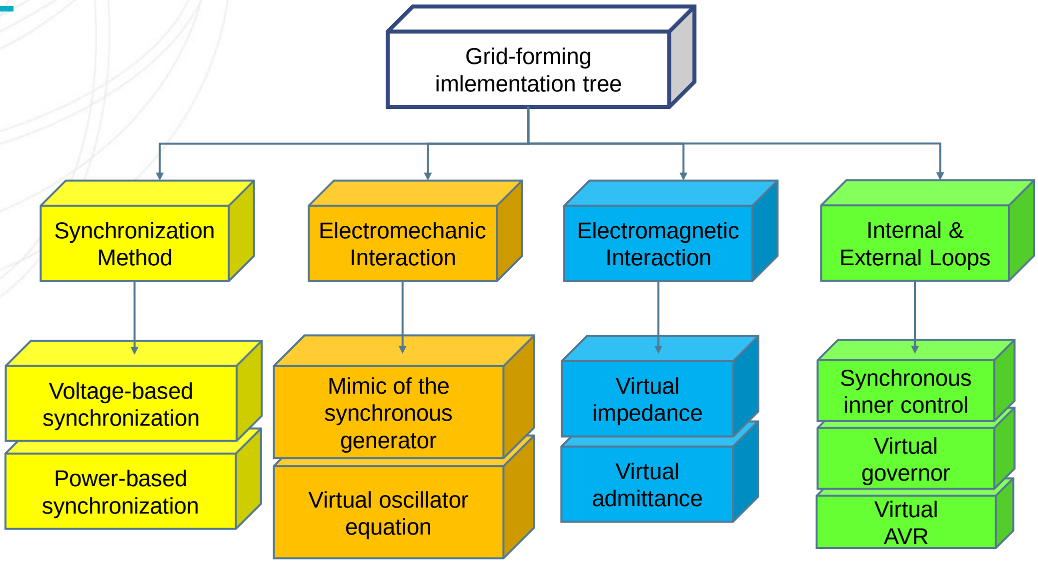
GFL control algorithm

Grid forming (GFM) power converter



GFM control algorithm

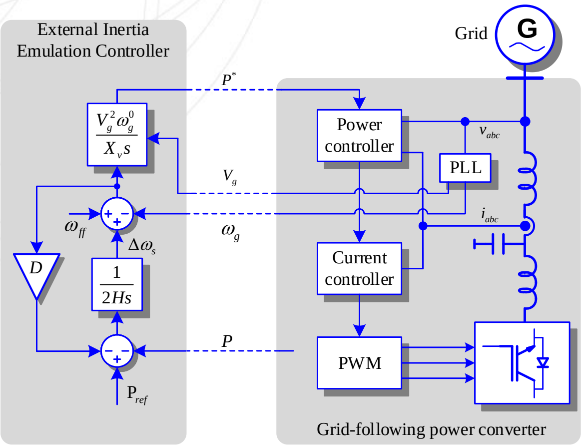
Implementing GFL and GFM power converters

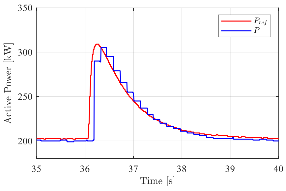


Grid-forming imlementation tree

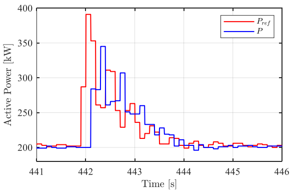
- Synchronization Method
  - Voltage-based synchronization
  - Power-based synchronization
- Electromechanic Interaction
  - Mimic of the synchronous generator
  - Virtual oscillator equation
- Electromagnetic Interaction
  - Virtual impedance
  - Virtual admittance
- Internal & External Loops
  - Synchronous inner control
  - Virtual governor
  - Virtual AVR

External inertia emulation controller





T_S=20ms



T_S=100ms

Ngoc Bao Lai, “Control of Power Converters in Modern Power Systems”, PhD. Dissertation. 2022

Virtual synchronous power plant controller

Power loop controller

$$G_P(s) = \frac{\Delta\omega}{\Delta P} = \frac{G_c}{s+\omega_c}$$

$$\omega_c = \frac{2 \cdot D}{\sqrt{\frac{X_v}{S_n} J \cdot \omega_g}}$$

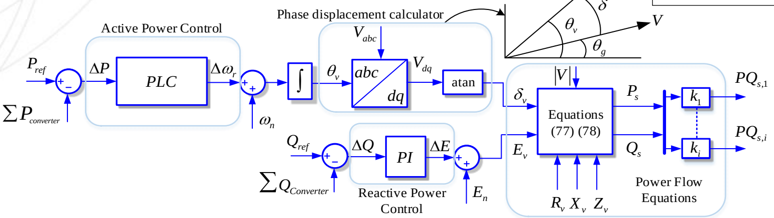
$$G_c = \frac{1}{J \cdot \omega_c \cdot \omega_g}$$

Phase integrator

$$\theta_v = \int \Delta\omega_r + \omega_n$$

Phase displacement calculator

$$\begin{bmatrix} V_d \\ V_q \\ 0 \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} \cos(\theta_v) & \cos(\theta_v) & \cos(\theta_v) \\ -\sin(\theta_v) & -\sin(\theta_v) & -\sin(\theta_v) \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \cdot \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}$$



Power distribution

$$k_{pi} = k_{qi} = \frac{S_i}{\sum_{i=1}^{N} S_i}$$

Reactive power controller

$$G_q(s) = \frac{\Delta E}{Q^* - Q_m} = \frac{K_p \cdot s + K_i}{s}$$

Electromotive force

$$E_v = E_n + \Delta E$$

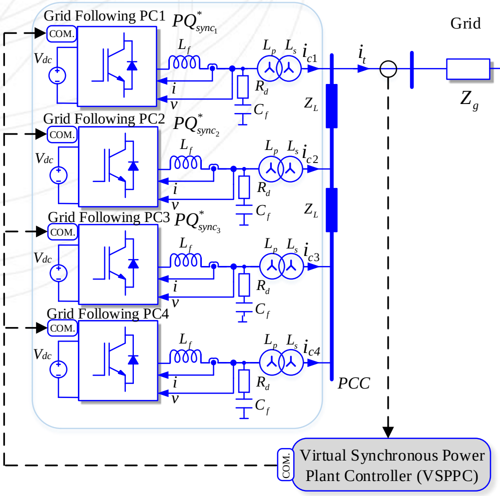
Power flow equations

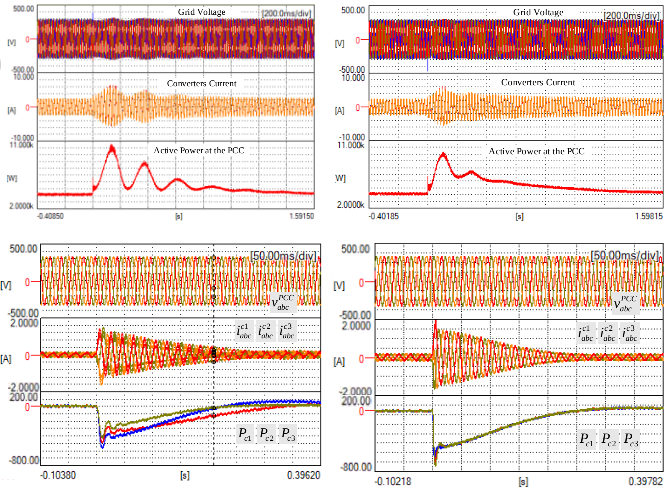
$$P_s = \frac{V_{PCC}}{R_v^2 + X_v^2}\left[R_v\left(V_{PCC} - E_v\cos(\delta_v)\right) + X_v E_v \sin(\delta_v)\right]$$

$$Q_s = \frac{V_{PCC}}{R_v^2 + X_v^2}\left[-R_v E_v \sin(\delta_v) + X_v\left(V_{PCC} - E_v\cos(\delta_v)\right)\right]$$

Andrés Tarraso, “Virtually Synchronous Power Plant Control”, PhD. Dissertation. 2022

Virtual synchronous power plant controller





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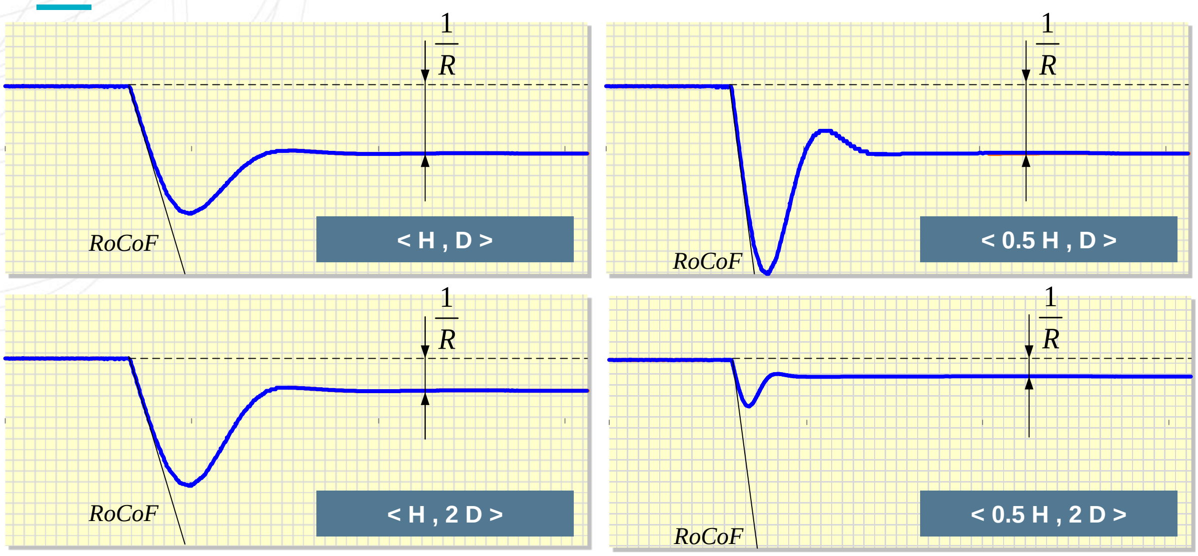
Virtual inertia and damping effects



WHERE
TOMORROW
BEGINS

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Thank you!!

For more info, please contact us at:
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