10th IERE Webinar on High Voltage Direct Current (HVDC), 15 October 2025
- HVDC Technology for the Next Generation Power Grid

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Grid Forming Control and Virtual Inertia Support by HVDC systems

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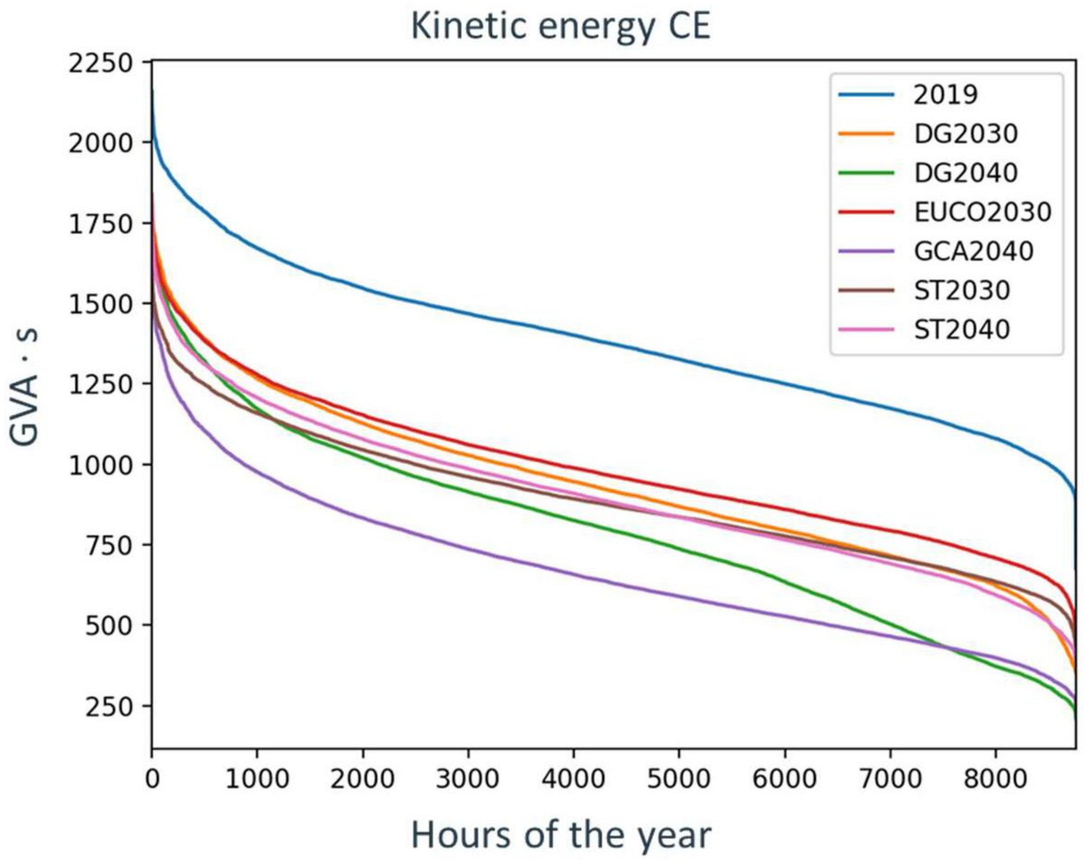
Outline

- Introduction
- Virtual inertia support from power electronic converters
  - Virtual inertia by "grid-forming" vs "grid-following" control
  - Virtual Synchronous Machines (VSMs) as an example of grid forming control
- Motivations and limitations of virtual inertia support from HVDC converters
- Summary and outlook

General development trend in power systems

- Increasing presence of power electronic converters
  - Renewable power generation
    - Wind turbines, photovoltaic generation etc.
  - HVDC transmission
- Decommissioning of thermal power plants
- Power converters do not inherently provide grid- forming capability or inertial response to support power system frequency regulation
  - ➢ **Reduced equivalent inertia in the power system**



ENTSO-E, "Inertia and Rate-of-Change-of-Frequency (RoCoF), Version 17, December 2020

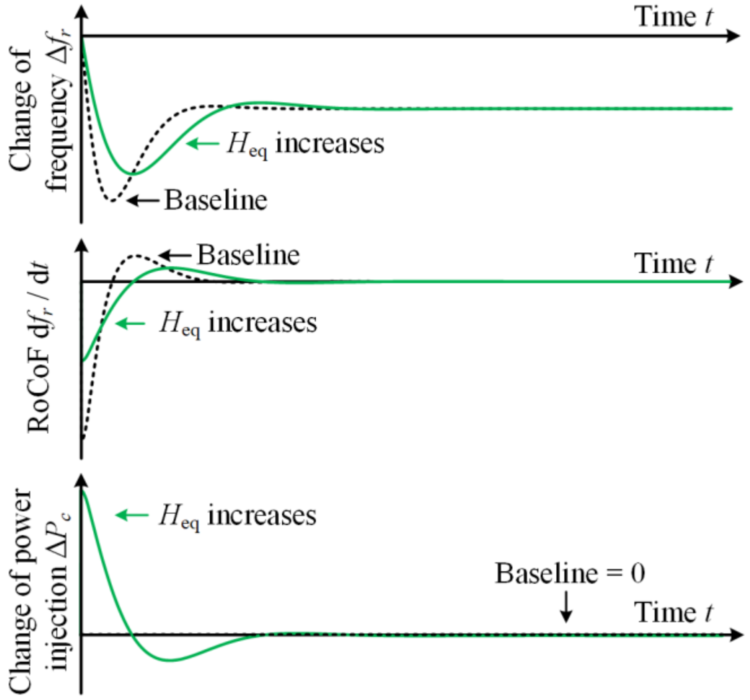
The role of inertia in power systems

- Limits the frequency transients in response to disturbances
  - Provides power response proportional to the frequency derivative

$$\Delta p = J\omega_r \frac{d\omega_r}{dt}$$

- Challenges with reduced inertia in grids with remaining traditional power plants:
  - Reduced minimum frequency (Nadir) in response to disturbances
  - Increased maximum Rate-of-Change-of-Frequency (RoCoF)

Idealized response to a loss of generation

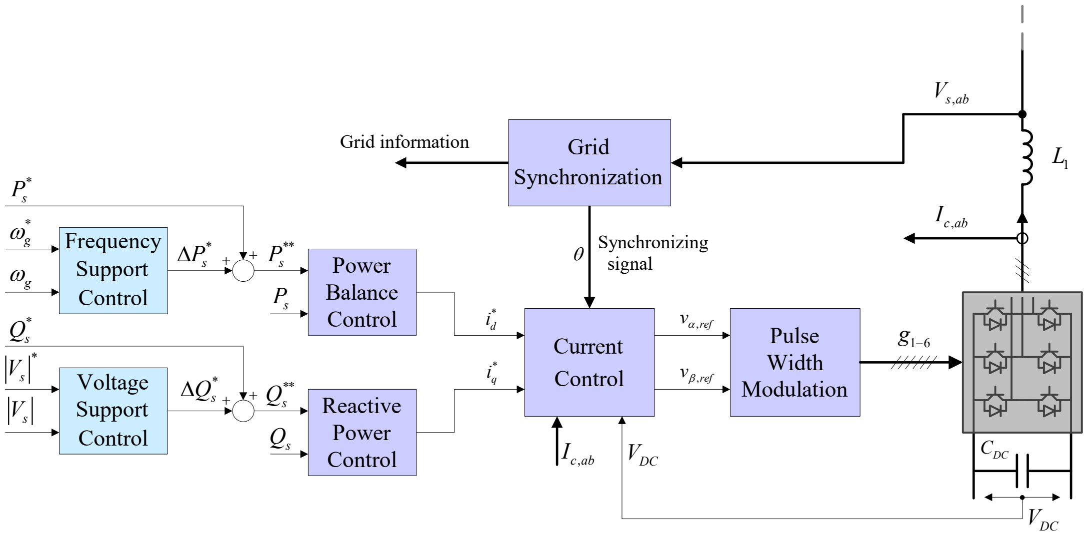


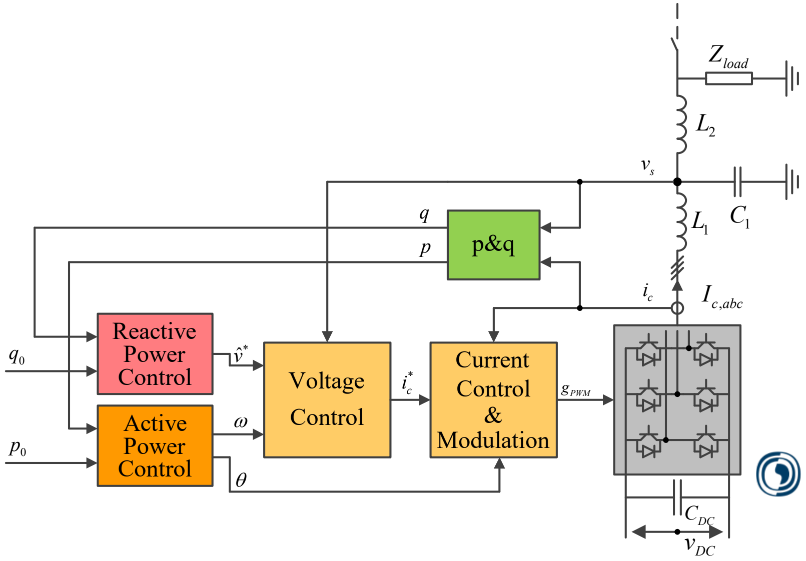
J. Fang, H. Li, Y. Tang, F. Blaabjerg, " On the Inertia of Future More-Electronics Power Systems," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, Vol. 7, No. 4, pp.2130-2146, December 2019

Control of power converters in power systems

- "Grid-following" converters
  - **Synchronization to the measured grid voltage**
    - Usually by a Phase Locked Loop (PLL)
  - Usually based on inner loop current control
  - **Power control by active current component**
  - Grid support functionality by auxiliary control loops
  - Stability challenges in "weak grids"

- "Grid-forming" converters
  - Capability for **voltage and frequency control**
    - Inherently capable of islanded operation
  - Power-balance-based synchronization mechanism
  - **Power control via voltage phase angle**
  - Outer loop control sharing of active and reactive power
  - Challenges with voltage control in "strong grids"





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Grid-forming control vs virtual inertia

- Grid forming control can include inherent inertia emulating features
  - Example: Virtual Synchronous Machines
- Virtual or synthetic inertia can be implemented as auxiliary function in grid-following converters
  - ➢ Frequency-derivative-based inertia emulation (df/dt IE)
  - Does not imply grid-forming capability

Synchronous Machine swing equation:

$$J\omega_r \frac{d\omega_r}{dt} = p_{mech} - p_{em}$$

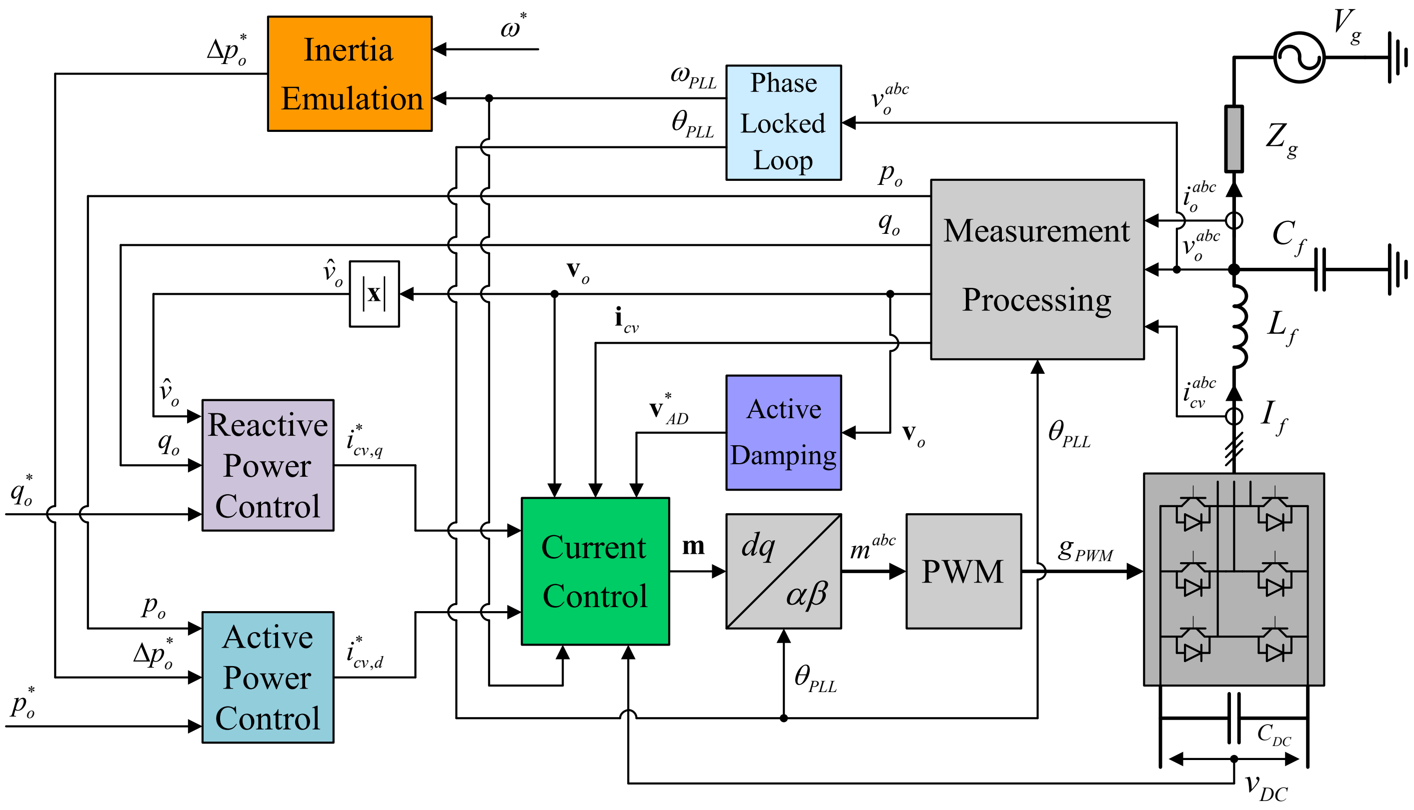
Equivalent response to enforced frequency variations:

$$\Delta\tau_{VI} \approx \Delta p_{VI} \approx J_{VI} \frac{d\omega_g}{dt}$$

Frequency-derivative-based inertia emulation

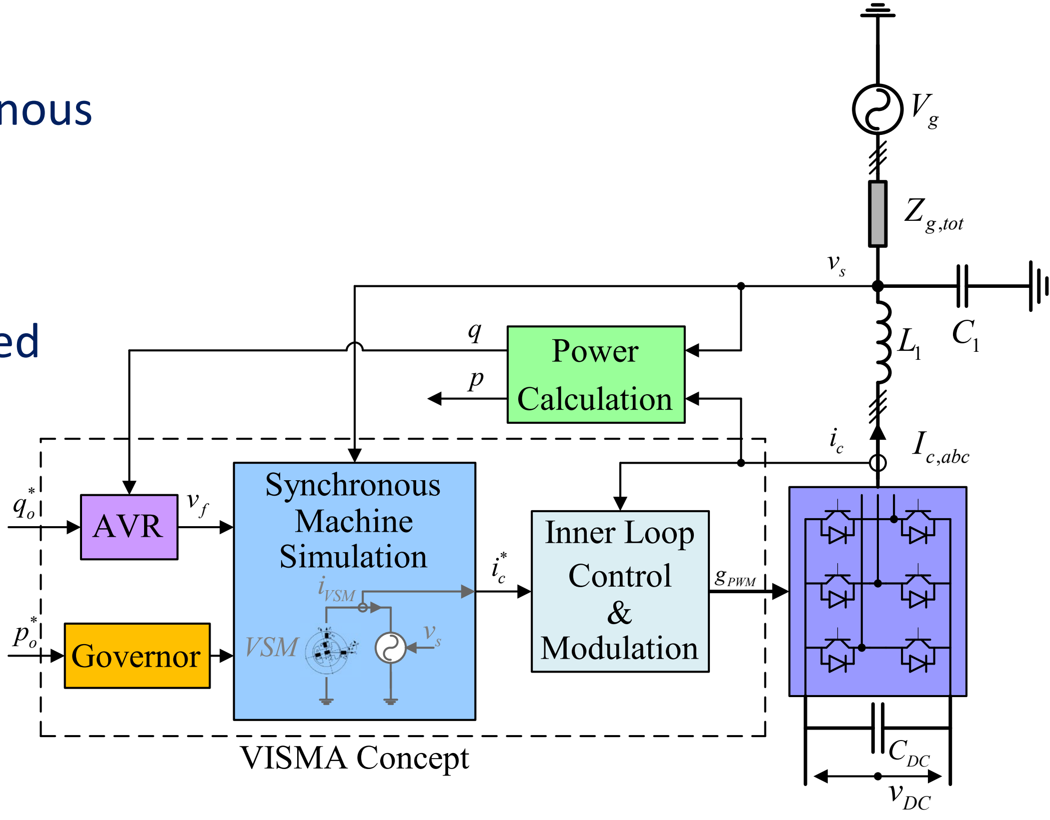
- Conventional control structure with:
  - Grid synchronization by PLL
  - Inner loop current controllers and active damping
  - Outer loop PI controllers for active and reactive power control
- Inertia emulation
  - Power reference calculated from the measured grid frequency and its (filtered) derivative:

$$\Delta p_o^*(s) = -k_J \frac{s\omega_{LPf}}{s+\omega_{LPf}} \omega_{PLL}(s) + k_\omega\left(\omega^* - \omega_{PLL}(s)\right)$$



Virtual Synchronous Machines for grid-forming control

- First publication controlling a converter as a Virtual Synchronous Machine (VISMA) by Beck and Hesse in 2006
- Internal simulation of a Synchronous Machine (SM) model
  - Simulated machine model provided current references used for converter control
- **Main purpose: Emulate the main operational characteristics of synchronous machines**
  - **Inertial dynamics (inertia and damping)**
  - **Grid forming functionality**
- The first proposals had higher detailing level than necessary
- Many implementations proposed in literature
  - Generally referred to as Virtual Synchronous Machines (VSMs)



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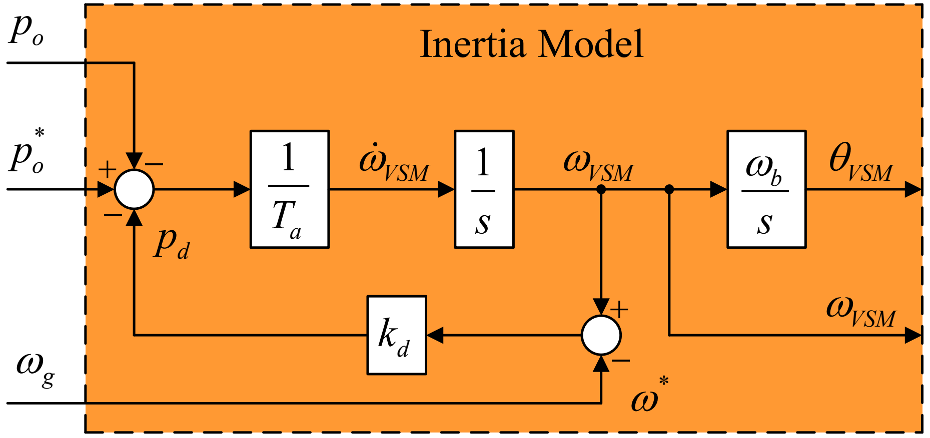
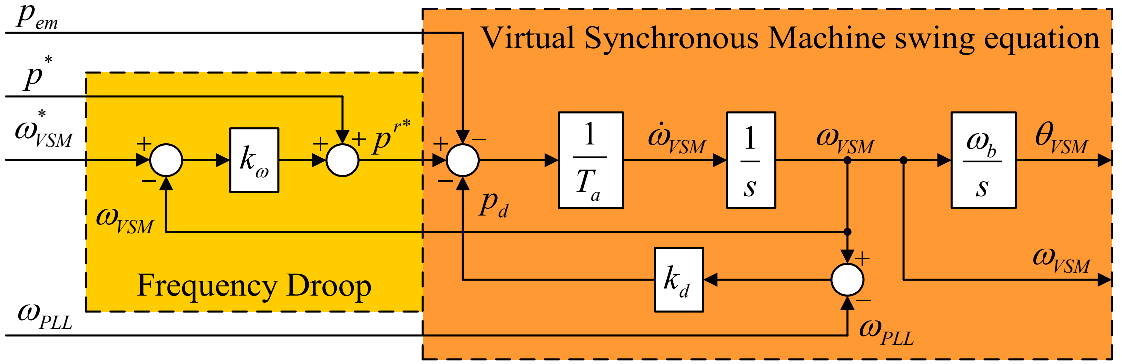
Basis for Virtual Synchronous Machine (VSM) control

- Synchronization mechanism and power control based on emulation of SM swing equation
  - Based on torque or power balance
  - Linearized power balance is simpler for VSM applications:

$$\frac{d\omega_{VSM}}{dt} = \frac{p_o^*}{T_a} - \frac{p_o}{T_a} - \frac{k_d\left(\omega_{VSM} - \omega_g\right)}{T_a}$$

- Ensures grid synchronization and inertial response to grid frequency variations
- Typically combined with a simple frequency droop ('governor') function





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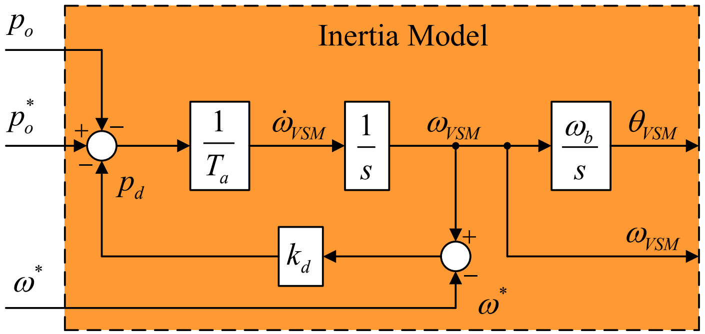
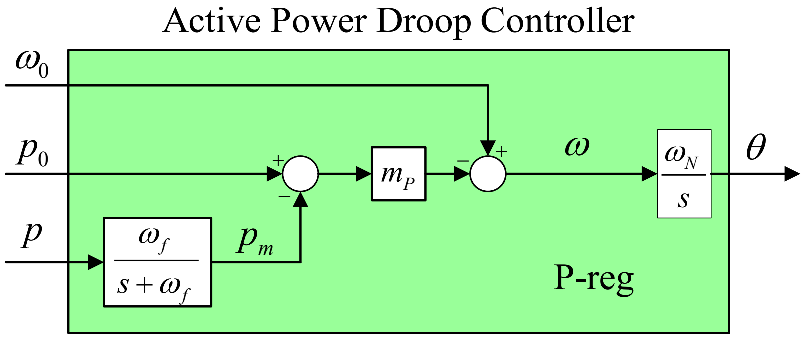
VSM as example of grid forming control

- VSM-based can be considered a sub-group of grid-forming control
  - A characteristic feature is the explicit emulation of inertia and damping
- Equivalence between VSM-based control and power-frequency droop:





$$\underbrace{\frac{1}{\omega_f m_p} s \cdot \omega}_{\text{Inertia term}} = p_0 - p_{el} - \underbrace{\frac{1}{m_p}\left(\omega_{pu}^* - \omega_{g,pu}\right)}_{\text{Damping term}}$$

$$T_a = \frac{1}{\omega_f m_p}, \qquad k_d = \frac{1}{m_p}$$

Salvatore D'Arco, Jon Are Suul, "Equivalence of Virtual Synchronous Machines and Frequency-Droops for Converter-Based MicroGrids," in *IEEE Transactions on Smart Grid*, Vol. 5, No. 1, January 2014, pp. 394-395

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Main differences between VSM and df/dt IE

- Virtual synchronous machines include explicit emulation of swing equation
  - Emulates power-balance-based grid synchronization mechanism of a synchronous machine
    - ➢ **Inherent grid forming capability**
    - ➢ **Explicit emulation of inertial dynamics**
    - ➢ Can operate in the same conditions as a synchronous machine (grid connected, islanded, paralleled, black-start etc.) if a dispatchable energy source is available
- Inertia emulation based on df/dt measurement:
  - Inertial response expressed as an incremental change of power reference
    - ➢ Simple to implement in conventional control systems of grid following converters
  - Depends on conventional grid synchronization and control
    - ➢ **No inherent grid forming capability**

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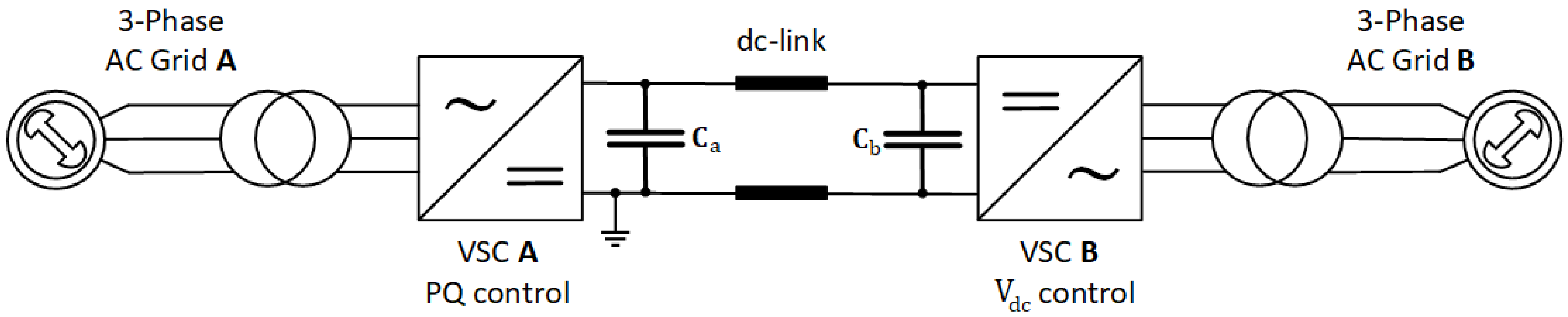
Grid forming control of HVDC converters

- Main motivations
  - High power rating from a single unit
    - Comparable size and influence on local grid as traditional large generation plants
  - High controllability of Modular Multilevel Converters (MMC)-based HVDC terminals
  - Typically customized design and control
  - Compatible with requirements for black-start capability
- Challenges
  - Current limitations and energy availability for providing inertial response
  - Power and energy availability for compensating load variations
  - Conflict between grid forming control and dc voltage control
  - Need for energy storage for providing grid forming functionality without other dispatchable sources



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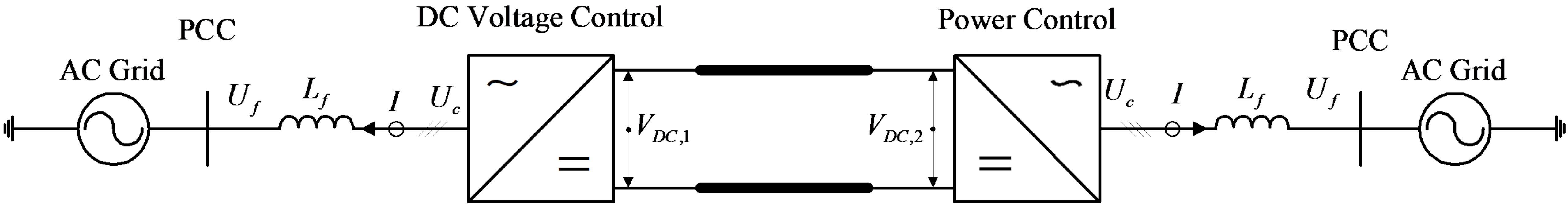
Virtual inertia from HVDC systems

- Limited energy for inertia emulation available in cables and capacitors
- Power-controlled converter terminals:
  - Energy for inertia emulation extracted from dc-voltage controlled terminal
  - Requires transient power exchange between interconnected power systems
- DC-voltage-controlled converter terminal
  - Conflict between inertia emulation and dc voltage control
  - Need for additional energy buffer?



Summary and outlook

- Virtual inertia from HVDC terminals in modern low-inertia power systems
  - Promising opportunity due to high power rating and high controllability
  - Wide range of control schemes proposed or under development – from academia and industry
    - Feasible with "grid-following" as well as "grid-forming" control
    - Different stability characteristics but equivalent response for inertia emulation
  - Main limitations are related to energy availability and dispatchability
- Open research topics
  - Required share and functionality of grid-forming converters in modern power systems
  - Need for virtual inertia for supporting remaining traditional generation units
  - Optimal location and transient response of converter units for providing virtual inertia
  - Converter control during fault conditions (including balanced and unbalanced faults)
  - Required changes to power system protection and operation with increasing share of converters

Thank you for your attention!

Questions?

References

- J. Fang, H. Li, Y. Tang, F. Blaabjerg, " On the Inertia of Future More-Electronics Power Systems," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, Vol. 7, No. 4, pp.2130-2146, December 2019
- H.-P. Beck, R. Hesse, "Virtual Synchronous Machine," in *Proceedings of the 9th International Conference on Electrical Power Quality and Utilisation*, Barcelona, Spain, 9-11 October 2007, 6 pp.
- Y. Chen, R. Hasse, D. Turschner, H.-P. Beck, "Comparison of methods for implementing virtual synchronous machine on inverters," in *Proceedings of the International Conference on Renewable Energies and Power Quality*, ICREPQ'12, Santiago de Compostela, Spain, 28-30 March 2012, 6 pp.
- [K. Sakimoto, Y. Miura, T. Ise, "Stabilization of a power system with a distributed generator by a virtual synchronous generator function," in *Proceedings of the 8th International Conference on Power Electronics – ECCE Asia*, Jeju, Korea, 30 May- 3 June 2011, 8 pp.
- Q.-C. Zhong, G. Weiss, "Synchronverters: Inverters That Mimic Synchronous Generators," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 4, April 2011, pp. 1259-1267
- Salvatore D'Arco, Jon Are Suul, "Virtual Synchronous Machines – Classification of Implementations and Analysis of Equivalence to Droop Controllers for Microgrids," in *Proceedings of IEEE PES PowerTech 2013*, Grenoble, France, 16-20 June 2013, 7 pp.
- Salvatore D'Arco, Jon Are Suul, "Equivalence of Virtual Synchronous Machines and Frequency-Droops for Converter-Based MicroGrids," in *IEEE Transactions on Smart Grid*, Vol. 5, No. 1, January 2014, pp. 394-395
- Salvatore D'Arco, Jon Are Suul, Olav. B. Fosso, "A Virtual Synchronous Machine Implementation for Distributed Control of Power Converters in SmartGrids," in *Electric Power System Research*, Vol. 122, May 2015, pp. 180-197
- O. Mo, S. D'Arco, J. A. Suul, "Evaluation of Virtual Synchronous Machines with Dynamic or Quasi-stationary Machine Models," in *IEEE Transactions on Industrial Electronics*, Vol. 64, No. 7, July 2017, pp. 5952-5962
- J. A. Suul, S. D'Arco, "Comparative Analysis of Small-Signal Dynamics in Virtual Synchronous Machines and Frequency-Derivative-Based Inertia Emulation," in *Proceedings of the 18th International Conference on Power Electronics and Motion Control*, PEMC 2018, Budapest, Hungary, 26-30 August 2018, pp. 344-351
- S. D'Arco, T. T. Nguyen, J. A. Suul, "Evaluation of Virtual Inertia Control Strategies for MMC-based HVDC Terminals by P-HiL Experiments," in *Proceedings of the IEEE 45th Annual Conference of the Industrial Electronics Society*, IECON'2019, Lisbon, Portugal, 14-17 October 2019, pp. 4811-4818
- F. G. Puricelli, S. D'Arco, J. A. Suul, L. Piegari, "Evaluation of Inertia Emulation Strategies for DC-Voltage-Controlled and Power-Controlled Converter Stations in HVDC Interconnections," in *Proceedings of the 25th International Symposium on Power Electronics, Electrical Drives, Automation and Motion*, SPEEDAM 2020, Sorrento, Italy / Virtual Conference, 24-26 June 2020, pp. 832-838
- P. Garcia-Rosa, S. D'Arco, J. A. Suul, "Placement of virtual inertia from HVDC terminals based on a frequency deviation index," in Proceedings of the 2021 IEEE Madrid PowerTech, Madrid, Spain / Virtual Conference, 28 June – 2 July 2021, 7 pp.
- E. Sánchez-Sánchez, E. Prieto-Araujo, O. Gomis-Bellmunt, "The Role of the Internal Energy in MMCs Operating in Grid-Forming Mode" in *IEEE Journal of Emerging and Selected Topics in Power Electronics*, Vol. 8, No. 2, pp. 949-962, June 2020

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