CONTROL METHODS FOR PROVIDING VIRTUAL INERTIA FROM POWER CONVERTERS AND ANALYSIS OF OPERATION UNDER UNBALANCED CONDITIONS

Open workshop on Virtual Inertia from HVDC Converters in future power systems, 28. April 2022

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Outline

- Virtual inertia support from power electronic converters
  - Basic concepts of "grid-forming" and "grid-following" control
  - Virtual inertia by Virtual Synchronous Machines (VSMs) as grid forming control
  - Virtual inertia by "grid-following" control
  - Virtual inertia from "grid-forming" vs "grid-following" control
- VSM-based control under unbalanced conditions
  - Strategies for negative sequence current control
  - Examples of results during unbalanced conditions
- Summary and outlook

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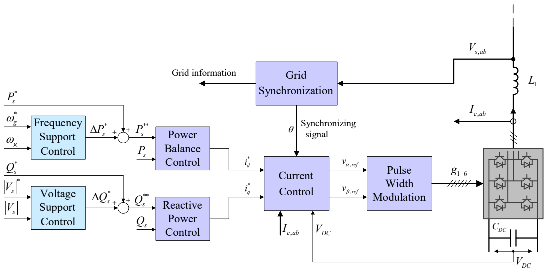
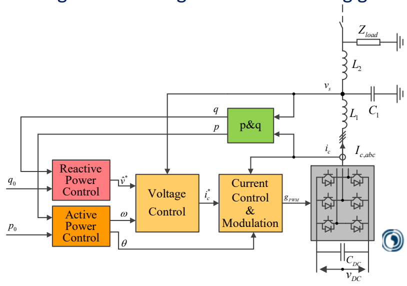
Control of power converters in power systems

- "Grid-following" converters
  - **Synchronization to the measured grid voltage**
    - Typically 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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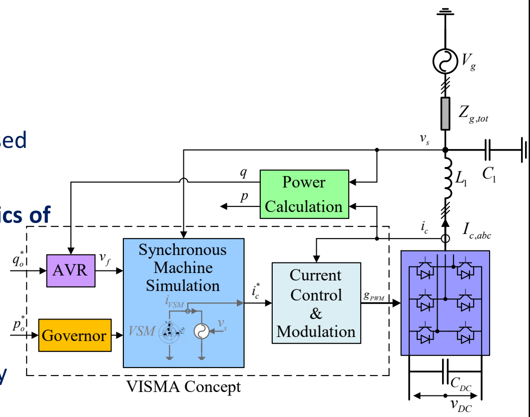
Virtual Synchronous Machines for grid-forming control

- First publication on Virtual Synchronous Machine (VISMA) concept by Beck and Hesse in 2006
- Internal simulation of a Synchronous Machine (SM)
  - Simulated machine model provided current references used for converter control
- **Main purpose: Emulate the main operational characteristics of synchronous machines**
  - **Inertial dynamics**
  - **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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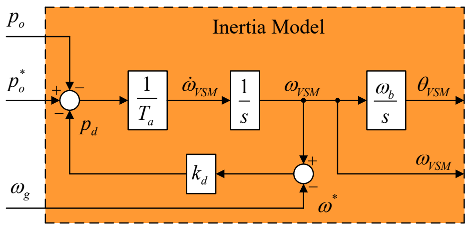
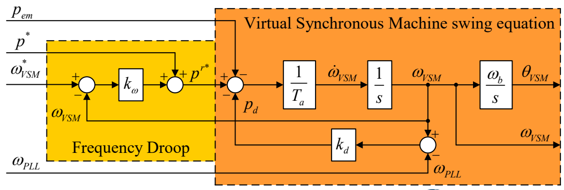
Basis for Virtual Synchronous Machine (VSM) control

- 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 power -frequency droop ('governor') function





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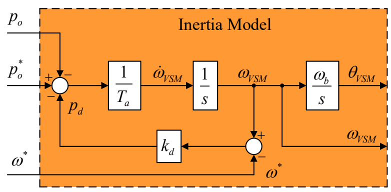
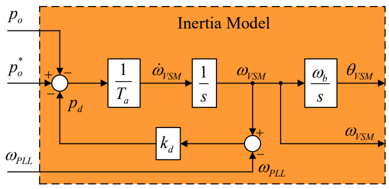
Swing equation damping for VSMs

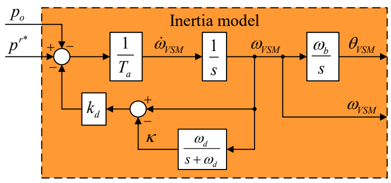
- Ideal swing equation depends on grid frequency:

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

- Implementation of damping has impact on dynamic response and steady-state operation
- Three main options:
  - Assuming a fixed grid frequency reference, $\omega_g = \omega^*$
    - Integrated damping and droop defined by the same parameter
  - Estimating the grid frequency from the voltage measurements (using PLL, FLL etc.), $\omega_g = \omega_{PLL}$
  - Internal estimation of the grid frequency $\omega_g = \omega_{VSM} H_{est}(s)$







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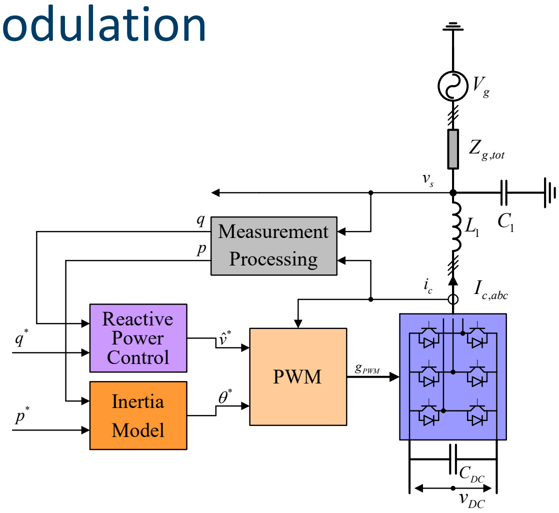
VSM with direct voltage modulation

- Virtual swing equation (inertia model) provides phase angle reference
- Voltage amplitude provided by reactive power or voltage control loop ("AVR")
- Voltage references used directly as reference for PWM operation of the converter
- No explicit current control for the converter or explicit overcurrent protection
- Simplest implementation:
  - Droop by damping coefficient (no separation between damping and droop and no explicit "governor" function
  - Commonly used for several concepts labelled as Virtual Synchronous Generators (VSGs), Synchronverters etc.



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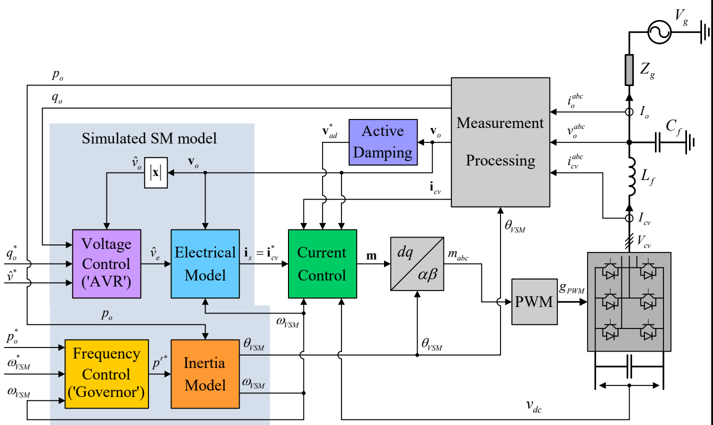
Current-Controlled VSM (CCVSM)

- Simulated inertia model
  - Provides virtual rotor frequency and phase angle for grid synchronization
  - Explicit "governor" function as a simple power-frequency droop
- Simulated electrical model:
  - Translates internal voltage reference into current references for converter control
  - Internal voltage reference provided by outer loop voltage control (AVR)



Example from: Olve Mo, Salvatore D'Arco, Jon Are 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

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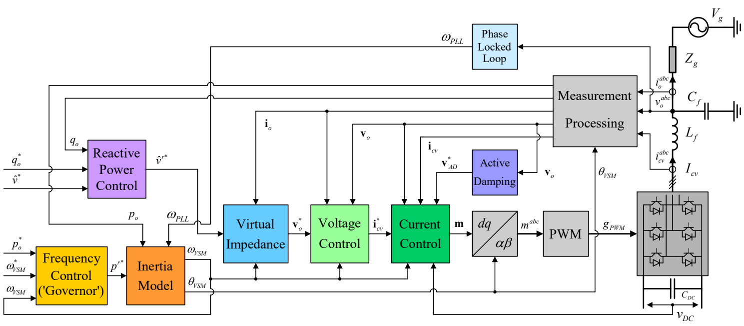
Voltage-Controlled VSM (VCVSM)

- Simulated inertia model
  - Provides virtual rotor frequency and phase angle for grid synchronization
  - "Governor" function can be a simple power-frequency droop
- Outer loop control of reactive power and voltage:
  - Provides voltage reference for closed loop voltage control
  - Virtual impedance is necessary for stable operation in strong grids



Example from: 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

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Grid-forming control vs virtual inertia

- Grid forming control can include inherent inertia emulating features
  - For instance: VSM-based control or large filtering time-constant in power-frequency droop control
- 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 any grid-forming capability

Synchronous Machine swing equation

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

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Equivalent response to enforced frequency variations

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

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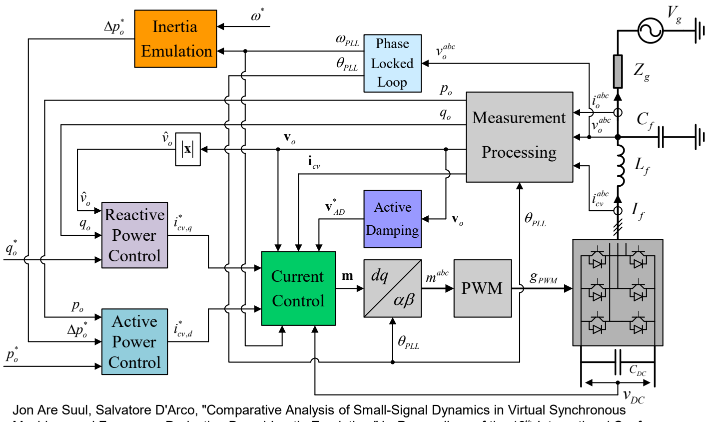
Frequency-derivative-based inertia emulation

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



Jon Are Suul, Salvatore 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

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

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Main differences between VSM and df/dt IE

- Virtual synchronous machines with 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 grid frequency measurement and conventional control
    - ➢**No inherent grid forming capability**

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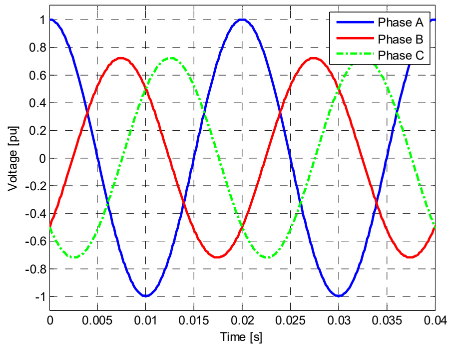
Virtual Inertia under unbalanced conditions

- Grid-following control
  - Strategies for grid synchronization and power control under unbalanced conditions are well established
  - Main challenge will be related to additional delays or filtering in the estimation of grid frequency and frequency derivative
- VSMs and grid-forming control
  - The fundamental challenges related to control of negative sequence components are similar to grid-following control – but the control objectives can be different



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Control objectives under unbalanced conditions

- Four controllable current components:

  $\mathbf{i}_d^+, \quad \mathbf{i}_q^+, \quad \mathbf{i}_d^-, \quad \mathbf{i}_q^-$

- In total 6 power components

  $\overline{p}, \quad \overline{q}, \quad \tilde{p}_{c2\omega}, \quad \tilde{p}_{s2\omega}, \quad \tilde{q}_{c2\omega}, \quad \tilde{q}_{s2\omega}$

$$\begin{bmatrix} \overline{p}_o \\ p_{c2\omega} \\ p_{s2\omega} \\ \overline{q}_o \\ q_{c2\omega} \\ q_{s2\omega} \end{bmatrix} = \begin{bmatrix} v_{o,d}^+ & v_{o,q}^+ & v_{o,d}^- & v_{o,q}^- \\ v_{o,d}^- & v_{o,q}^- & v_{o,d}^+ & v_{o,q}^+ \\ v_{o,q}^- & -v_{o,d}^- & -v_{o,q}^+ & v_{o,d}^+ \\ v_{o,q}^+ & -v_{o,d}^+ & v_{o,q}^- & -v_{o,d}^- \\ v_{o,q}^- & -v_{o,d}^- & v_{o,q}^+ & -v_{o,d}^+ \\ -v_{o,d}^- & -v_{o,q}^- & v_{o,d}^+ & v_{o,q}^+ \end{bmatrix} \begin{bmatrix} i_{v,d}^+ \\ i_{v,q}^+ \\ i_{v,d}^- \\ i_{v,q}^- \end{bmatrix}$$

- Possible to control up to four of the power components
  - Main control objectives are usually the average active and reactive powers
  - Two remaining degrees of freedom that can be utilized to control the power flow characteristics (i.e. the four oscillating power components)

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Negative sequence control strategies

- Relevant control objectives
  - Direct control of power flow characteristics by the negative sequence current components
    - Balanced Positive Sequence Current (BPSC) control
    - Constant Active Power (CAP) control – elimination of active power oscillations
    - Constant Reactive Power (CRP) control – elimination of reactive power oscillations
  - Impedance-based sharing of negative sequence loading
    - Negative sequence virtual impedance (NSVI) control
  - Negative sequence voltage control (NSVC)
- Suitable VSM-based control framework
  - Current Controlled VSM – simplest way of providing closed loop negative sequence current control
  - Current control in stationary frame to avoid delay of sequence separation

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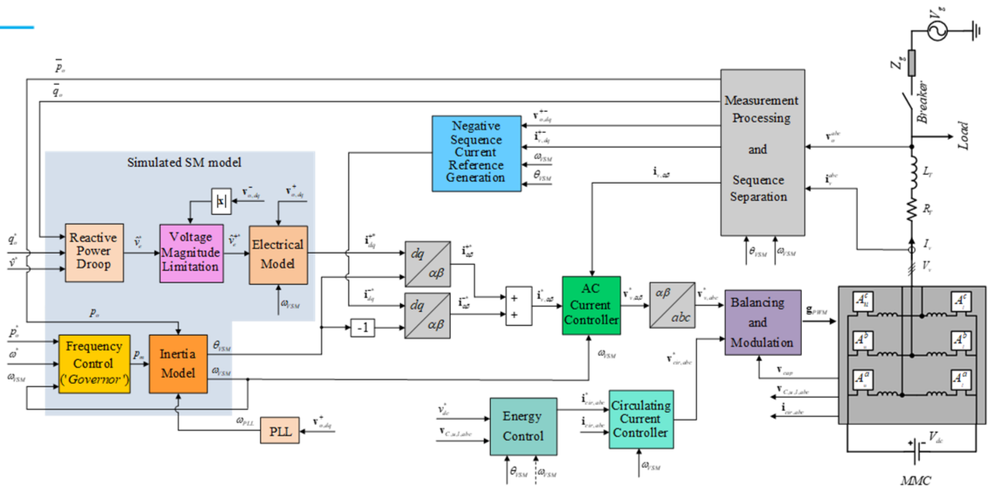
Control system overview



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Eros Avdiaj, Salvatore D'Arco, Luigi Piegari, Jon Are Suul,"Negative Sequence Control for Virtual Synchronous Machines Under Unbalanced Conditions" accepted for publication in IEEE Journal of Emerging and Selected Topics in Power Electronics, April 2022

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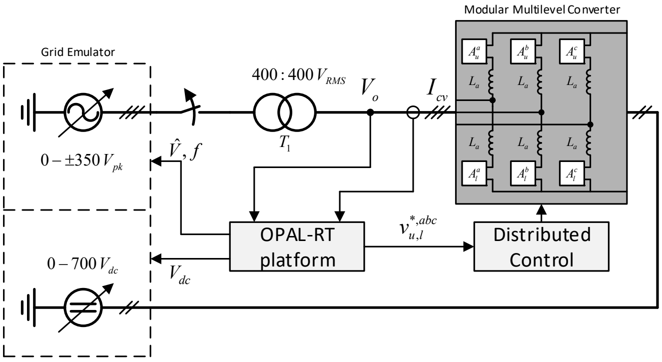
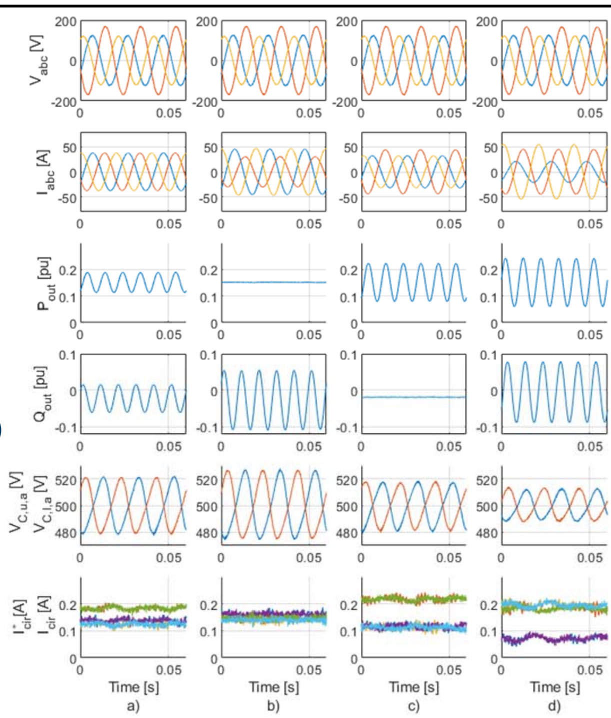
Experimental setup

- 50 kVA MMC prototypes
- Control implemented by OPAL RT
- Perturbations imposed by grid emulator



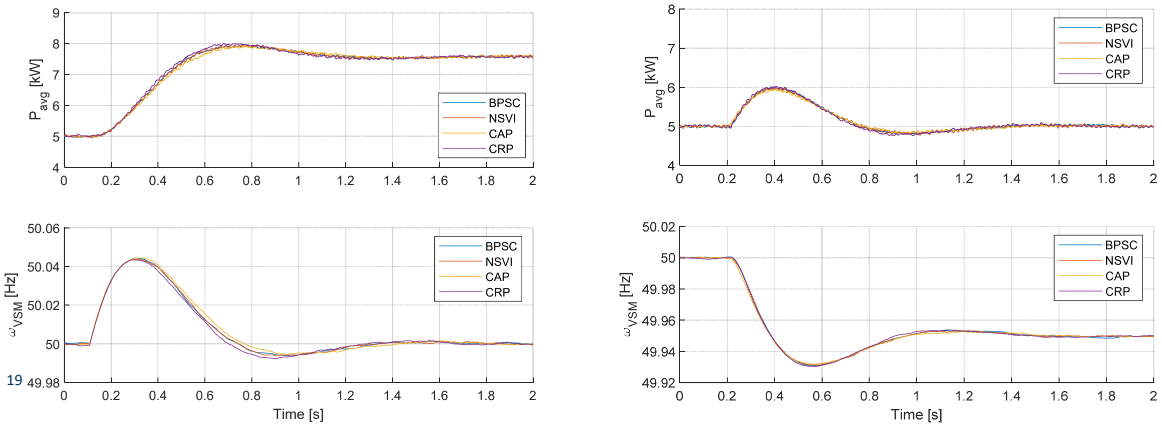
Steady-state response

- Test in strong grid conditions with
  a) Balanced positive sequence control (BPSC)
  b) Constant active power control (CAP)
  c) Constant reactive power control (CRP)
  d) Negative Sequence Virtual Impedance (NSVI)
- Performance as expected
- Negative Sequence Voltage Control is not applicable for strong grid conditions and is not tested



Demonstration of inertial response

- Test of power reference change and grid frequency perturbation
  - Almost identical inertial response independently of negative sequence current control



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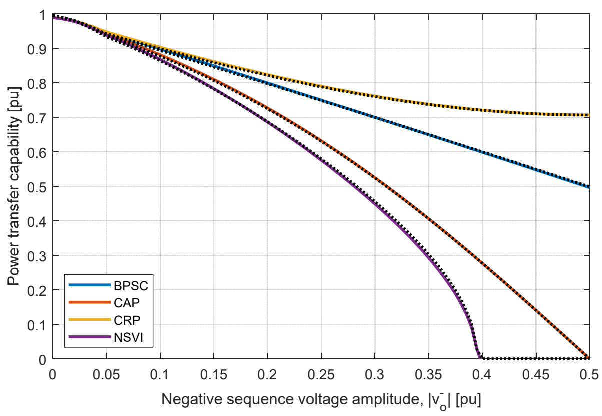
Power transfer capability limitations

- Imposing current amplitude limitation:

$$I_{\lim} = |i_v^+| + |i_v^-| = \sqrt{{i_{v,d}^+}^2 + {i_{v,q}^+}^2} + \sqrt{{i_{v,d}^-}^2 + {i_{v,q}^-}^2}$$

- Solving for the load angle that will lead to current amplitude equal to the current limit
- Result can be substituted back into expression for average power flow
- Plots illustrate power transfer capability with 1.0 pu current limit



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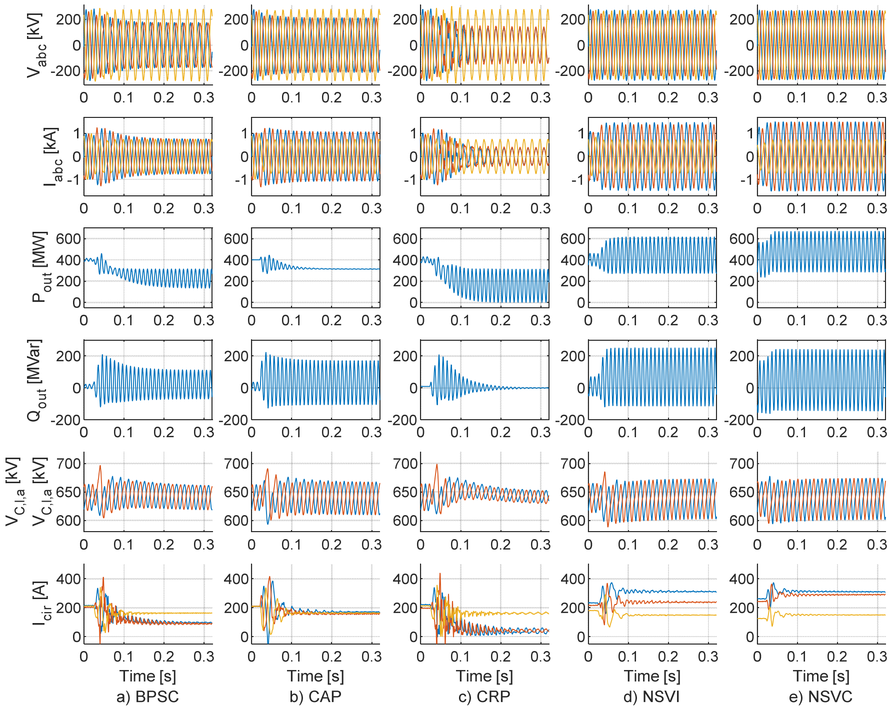
Example by simulation:

- Islanding with a local unbalanced load
- Highlights how BPSC, CAP and CRP result in unbalanced voltages of the islanded grid
- NSVI and NSVC are more suitable for islanded operation



Summary and outlook

- Virtual inertia can be provided by both "grid-following" and "grid-forming" converters
  - Similar effect on equivalent inertia but different operational characteristics and limitations
- Virtual Synchronous Machines as examples of "grid-forming" control
  - Three main classes of implementation: direct modulation, current controlled (CCVSM) or voltage controlled (VCVSM)
- Introduction to VSM control for unbalanced conditions
  - CCVSM with different options for control of negative sequence currents
- Open issues
  - Protection and current saturation under unbalanced conditions
  - Methods for modelling, analysis and tuning of MMC VSMs designed for unbalanced conditions
  - Interaction between multiple units or with grid following converters under unbalanced conditions

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