Recent advances with the VSM algorithm - a building block for a stable and well-damped electronic grid

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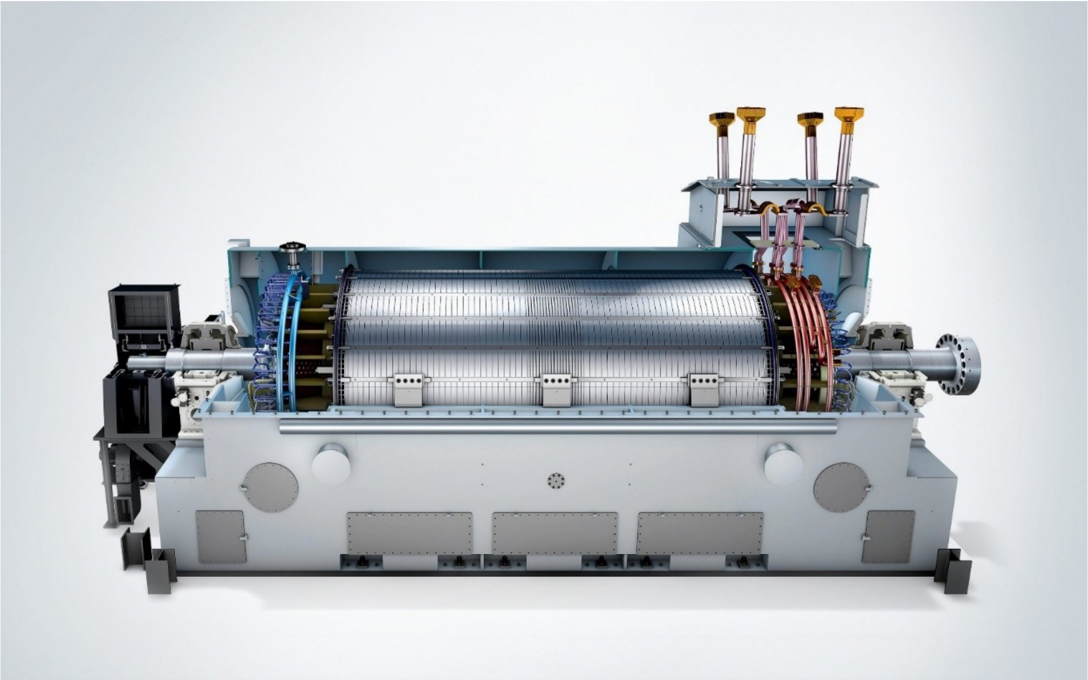
WinGrid Workshop, Warwick, October 2023

Traditional power generation

Thermal energy source

Mechanical power

synchronous generator



Electrical power

pic: Siemens

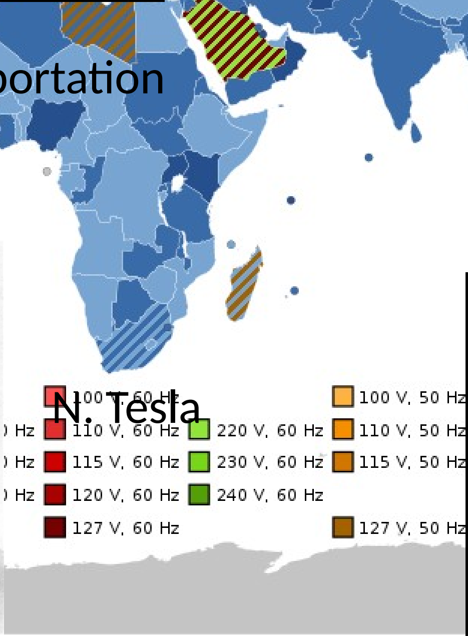
Most commonly grids are AC

Reasons for using AC:

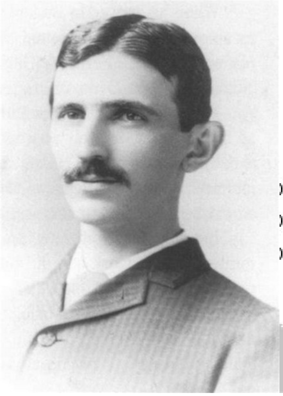
Easy generation

Easy transportation

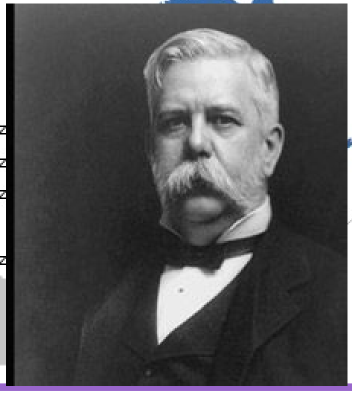
Easy transformation



T. Edison



N. Tesla



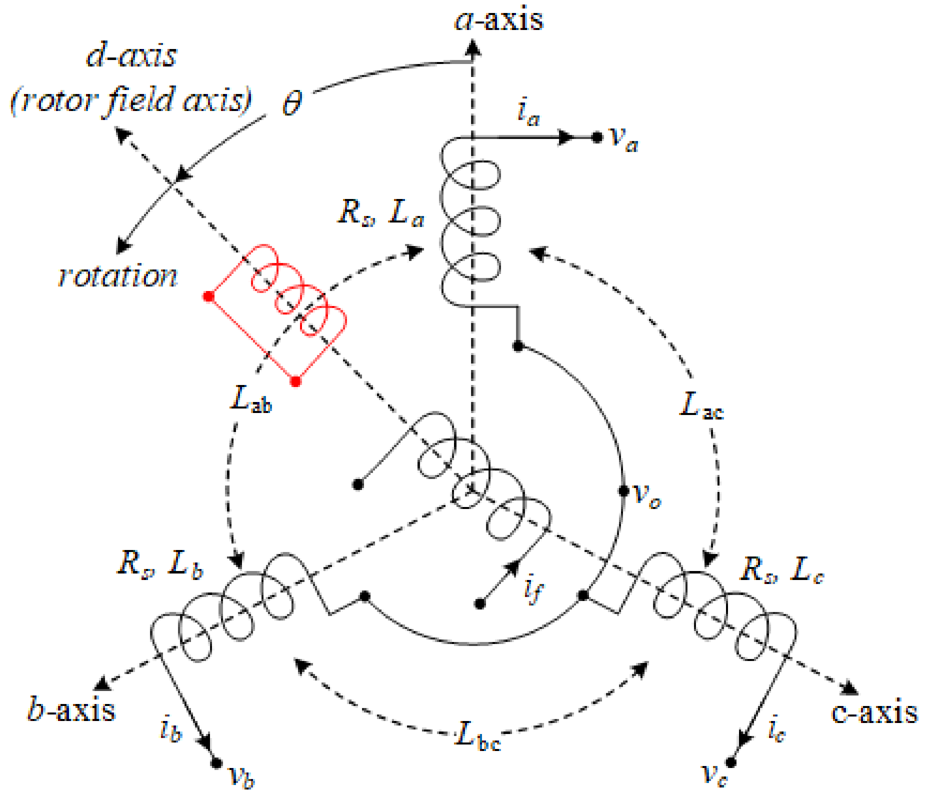
G. Westinghouse

Pics: Alstom, powerandcables.com, Siemens, giphy.com

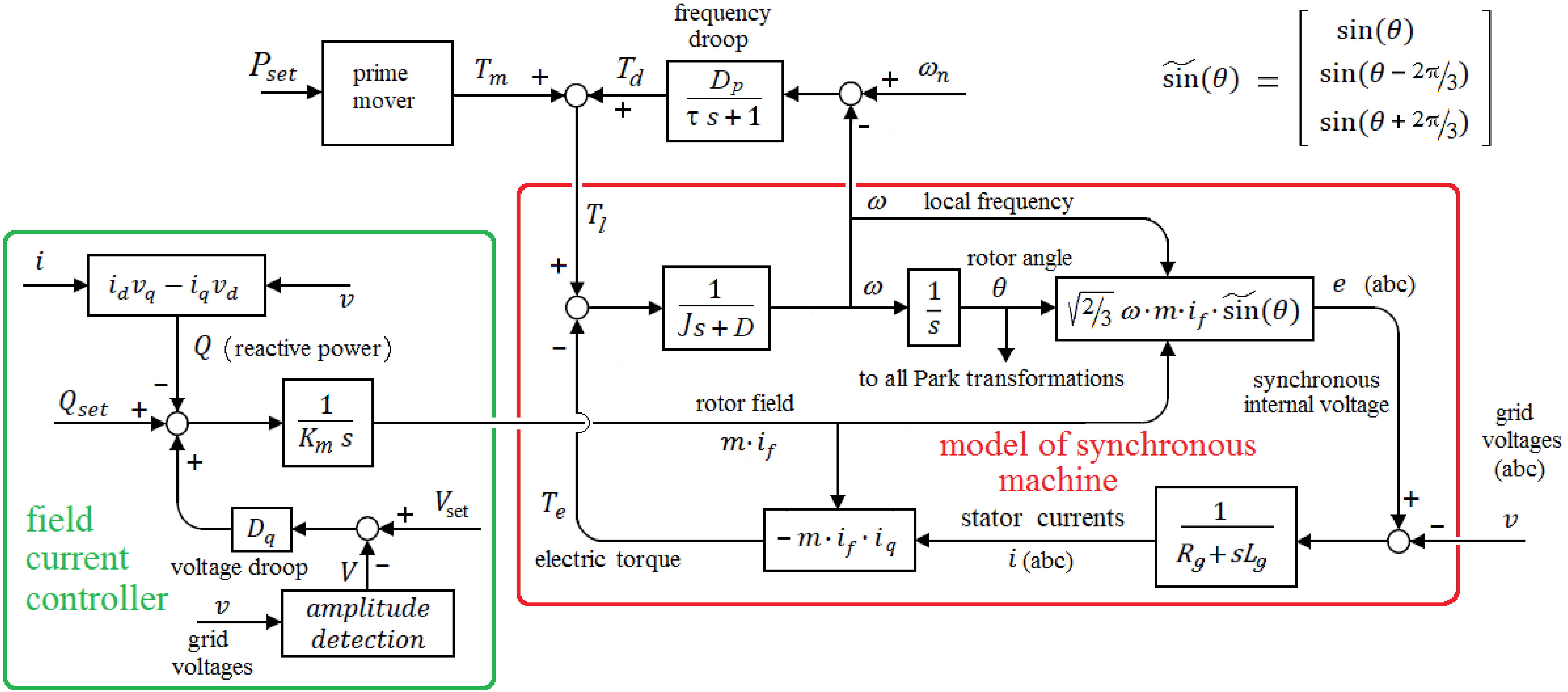
Synchrounous genartors (SG)

SG external appearance:

SG schematic representation:

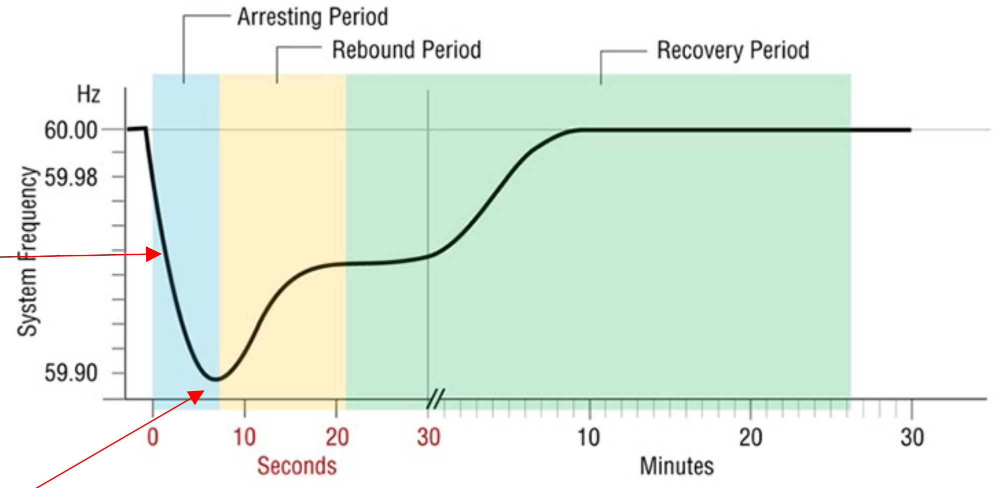


Simplified block diagram of a conventional SG with excitation control:



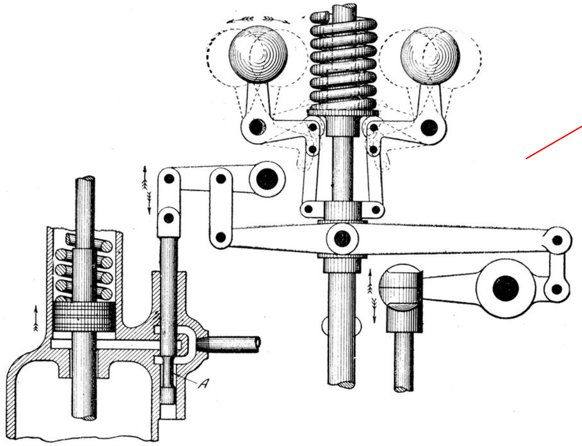
SGs connected together in a grid tend to synchronize! First explanation in 2012 (DB). Two main stabilizing mechanisms:

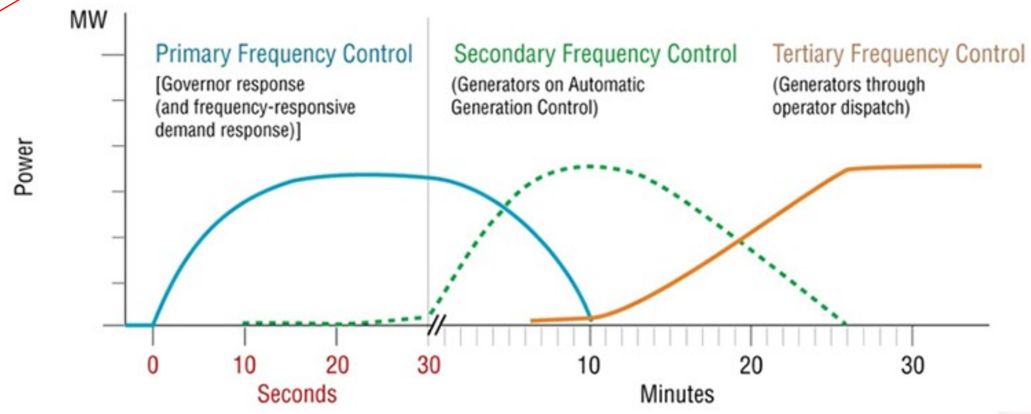
Inertia $E = \frac{1}{2} J \omega^2$



Frequency droop

$T = D_p(\omega - \omega_r)$





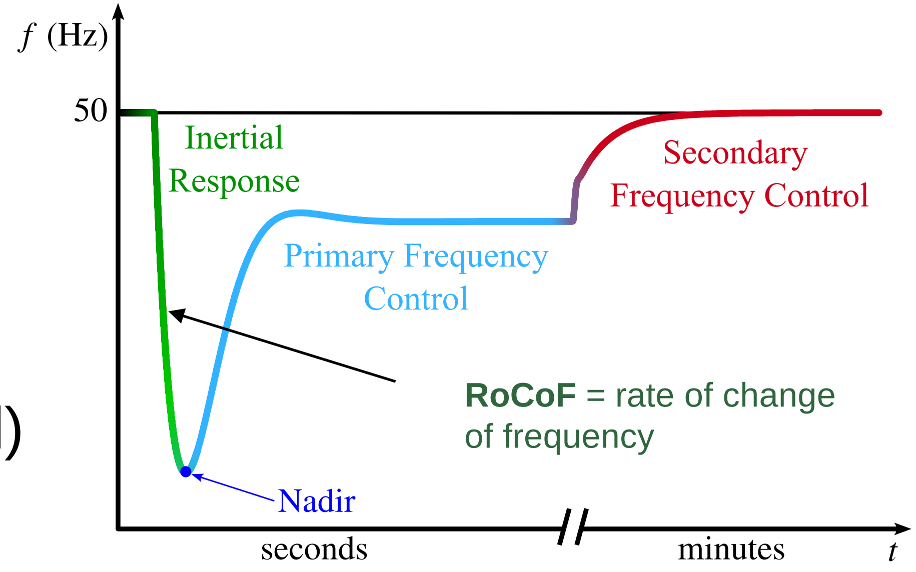
Source
Derr, Louis Cyclopedia of Engineering (Chicago, IL: American Technical Society, 1911)
https://etc.usf.edu/clipart/77800/77872/77872_governor_tbn.htm

https://www.e-education.psu.edu/ebf483/node/705
Source: Joe Eto, Lawrence Berkeley National Laboratory

Risks of conventional (power source) control for grid power converters

The frequency response in case of sudden overload (or generator loss) for a grid dominated by synchronous generators:

- The frequency drops to a minimum value (Nadir)
- The Nadir and RoCoF (Rate of Change of Frequency) depends on the energy stored in the total rotating mass (rotors of generators and turbines)
- The droop control takes action (primary frequency control)
- The frequency goes back to rated value thanks to the (slow) action of the secondary frequency control



In a grid with large penetration of static power converters, the total system inertia is drastically lowered and therefore the RoCoF increases while Nadir may drop too much, triggering protection systems for load shedding or generator disconnection, with the risk of losing stability.

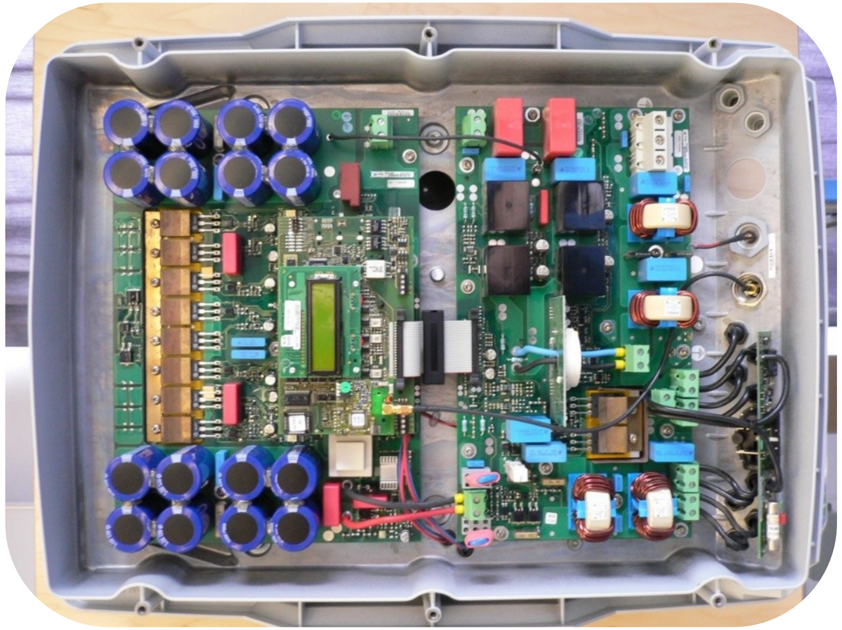
SG vs power electronic (PE) converters:

SG characteristics:

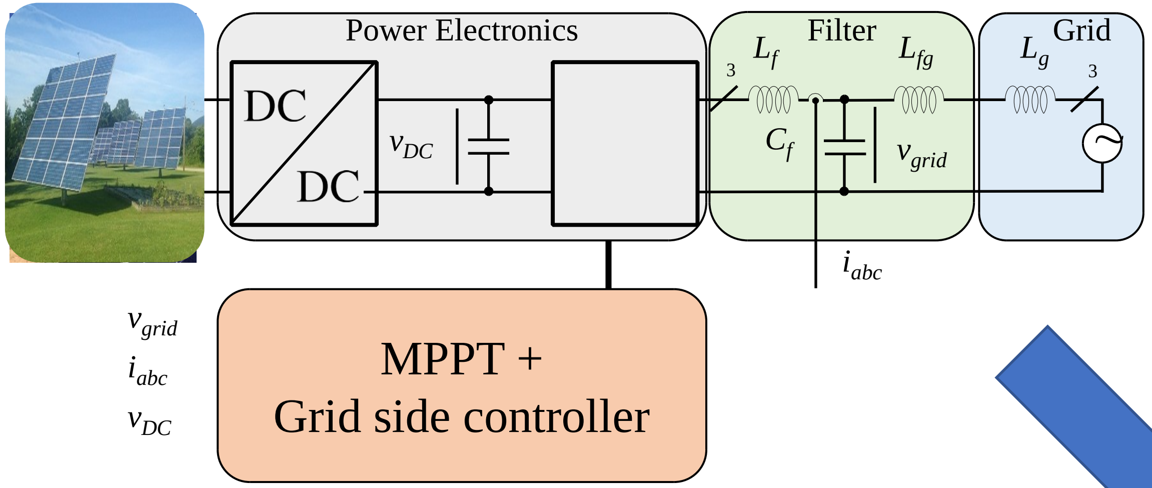
- Inertial behavior (mechanical rotor)
- Large short circuit current contribution
- Harmonic filtering

Conventional PE converters

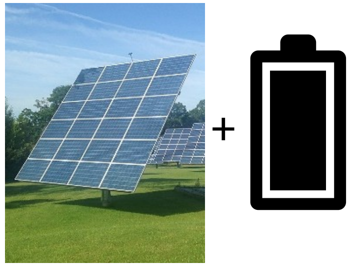
- No inertia (no rotating parts)
- Limited short circuit current (rated)
- Active filters for power quality improvement

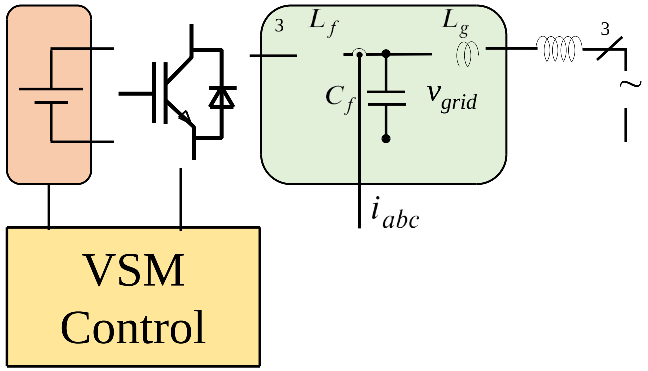


Conventional solar inverter:



VSM using some energy storage + same power electronics hardware:





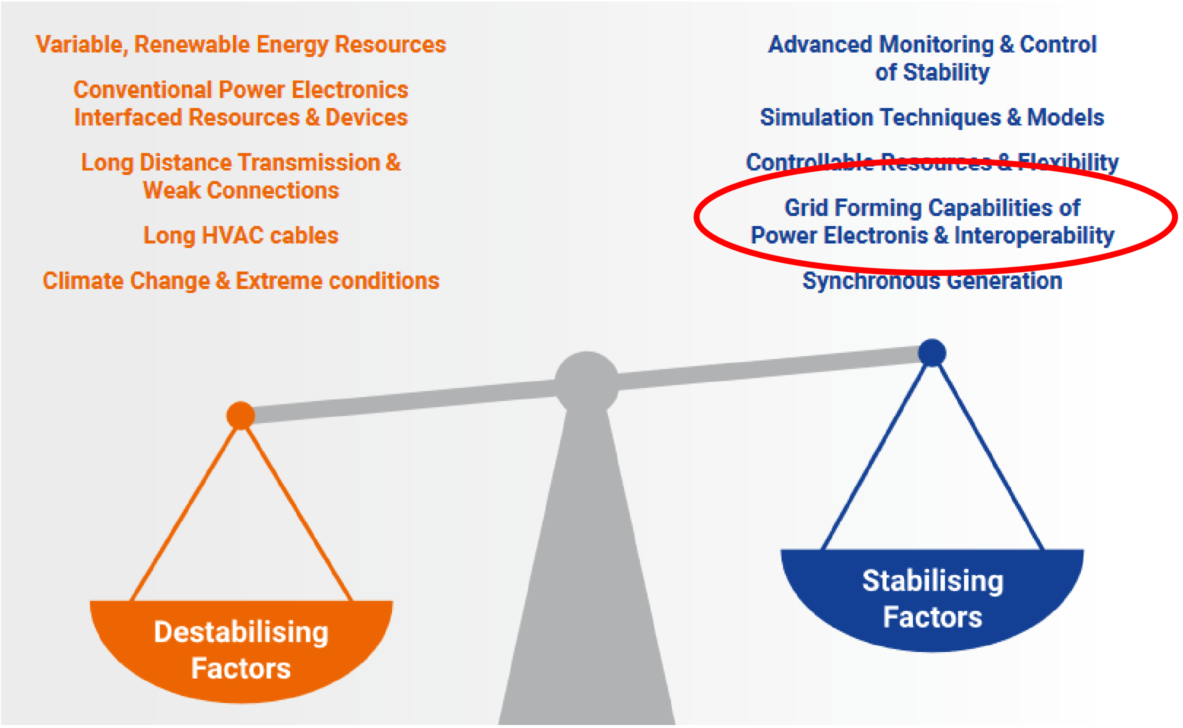
Control algorithm:

- Virtual inertia (mechanical emulation)
- Reactive support during faults
- Harmonic compensation
- Frequency & voltage droops

VSM Fields of Application

Renewable energy integration

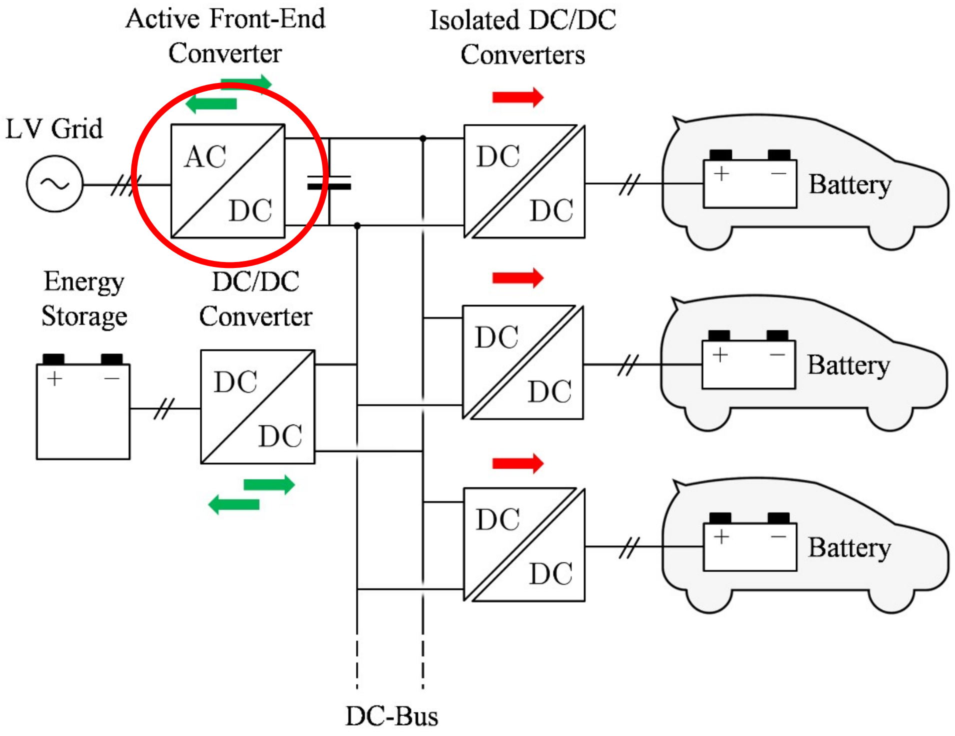
- Solar and wind farms
- Storage systems



ENTSO-E, "Stability Management in Power Electronics Dominated Systems: A Prerequisite to the Success of the Energy Transition", June 2022

Large aggregated loads

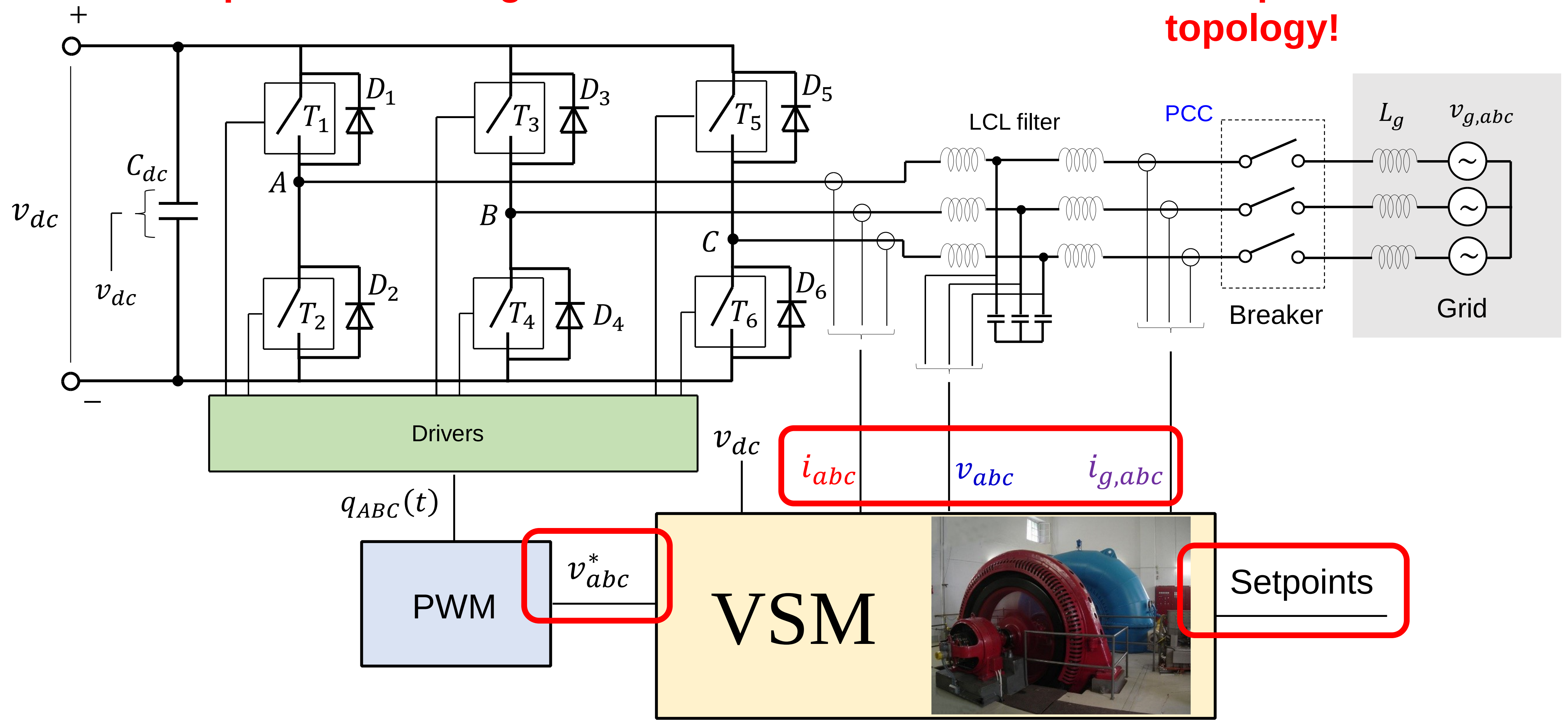
- Fast charging stations with V2G capability: provision of reactive power support, droops and inertia



Inverter architecture

Example: 2-level 3-legs inverter

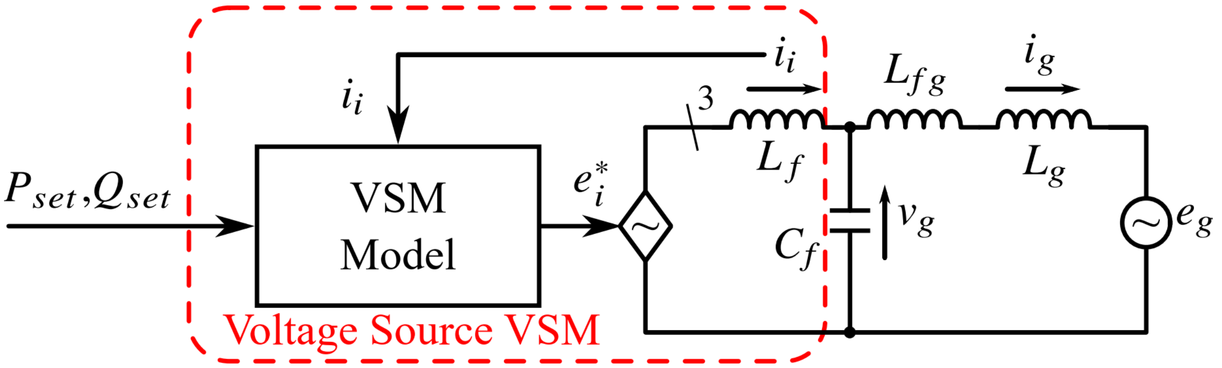
VSM does not depend on inverter topology!



Hardware and low-level control - two alternatives:

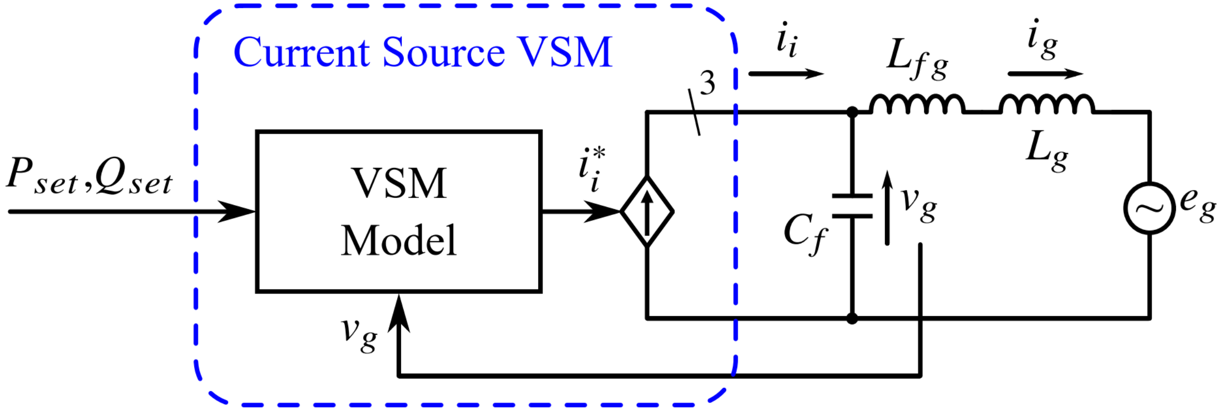
On ms scale, voltage source behavior:

- Simple control (open loop voltage)
- More suited for weak grids
- Difficult to limit current
- Stator inductance = Grid-side filter
- Very sensitive to measurement errors



On ms scale, current source behavior:

- Current limitation (closed loop)
- Fully tunable virtual stator
- More complex (current control)
- Issues with ultra-weak grids

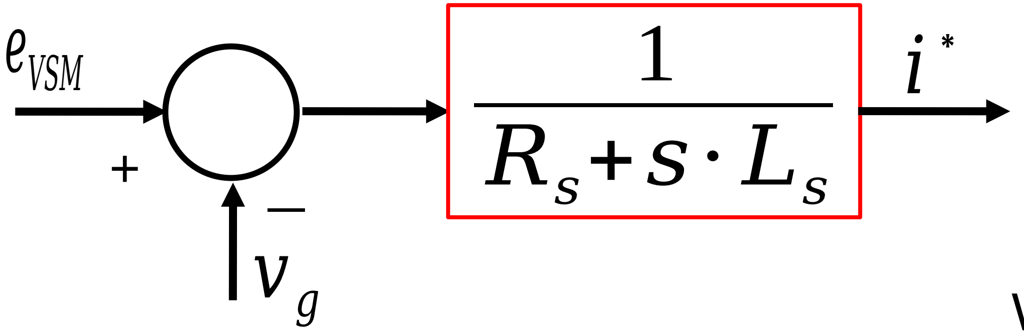


How to generate the reference output current *i** in a VSM

The version with current control is much better for immunity to noise and imbalance. To use it, we need to create a virtual impedance in the VSM, which in itself is a plus:

- Can be implemented in abc, αβ or dq frames
- Avoids numerical differentiation and low pass filter
- We can make the stator impedance much larger than the inverter filter impedance
- Current limitation is possible, without introducing distortion (clipping)

synchronous internal voltage from VSM algorithm, depends on excitation control



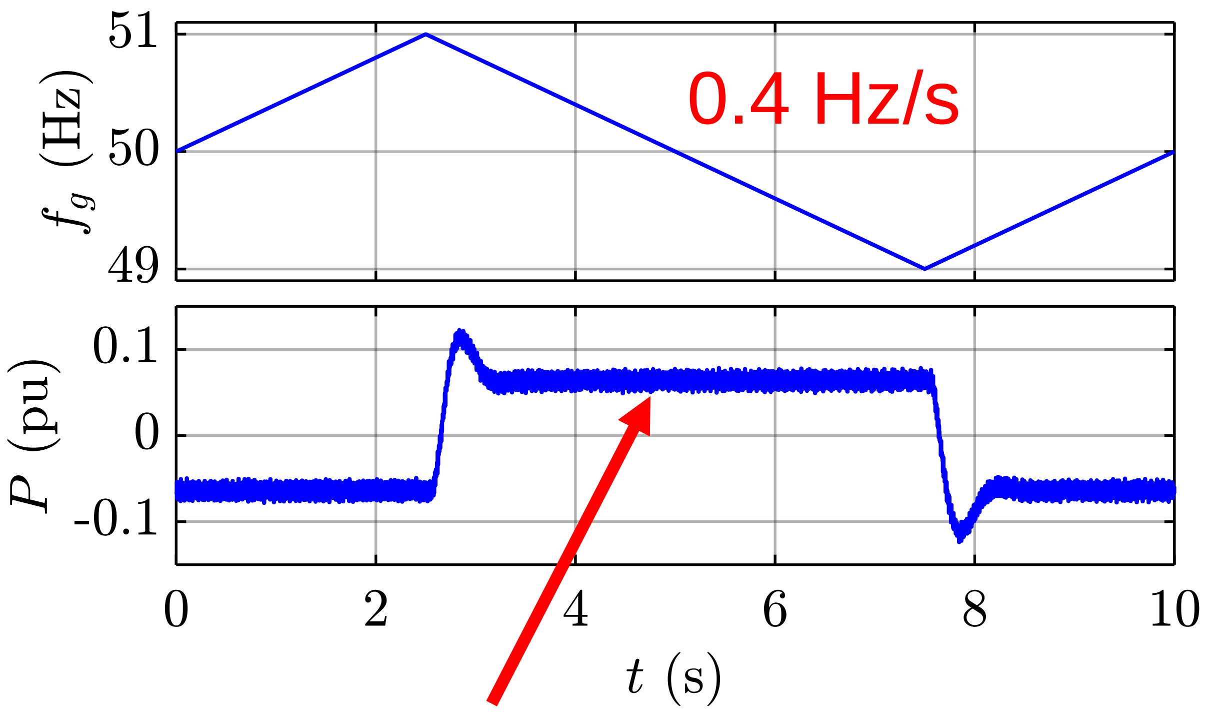
from grid voltage measurements

current limitation and then current loop references

We may use more complex impedance comprising virtual capacitor, tunable elements.

Frequency Support – test of inertial response

Triangular frequency Hz (s)



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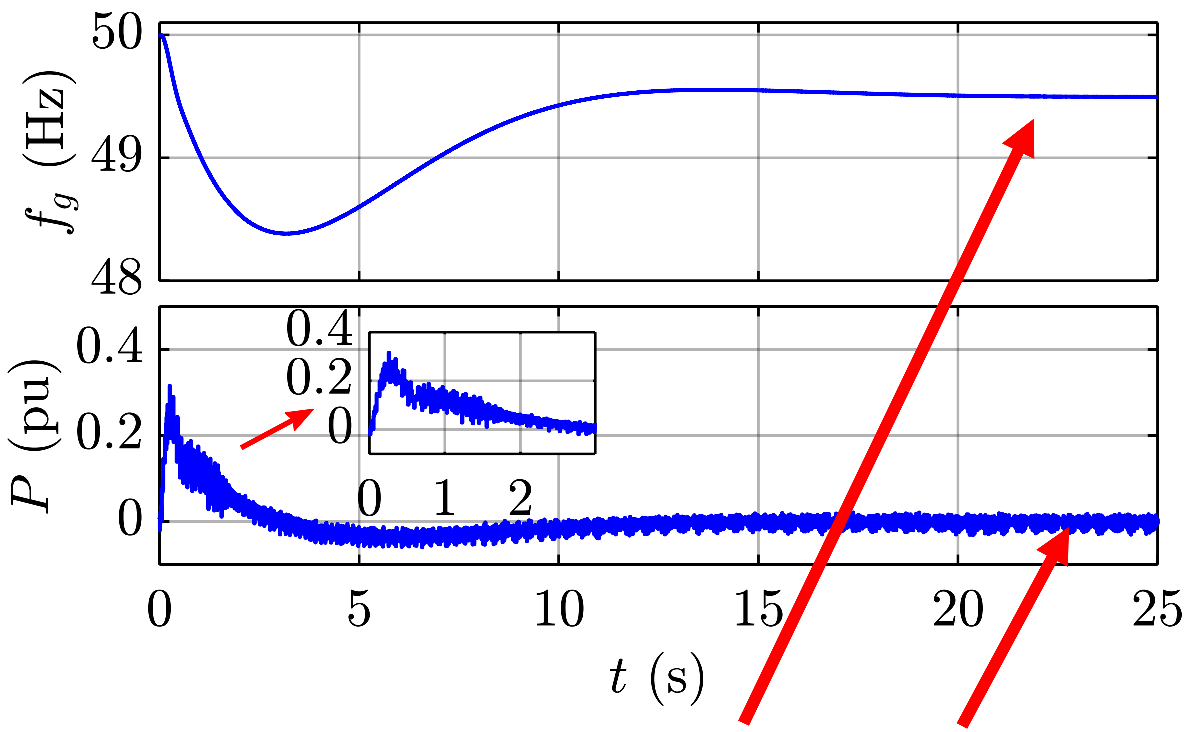
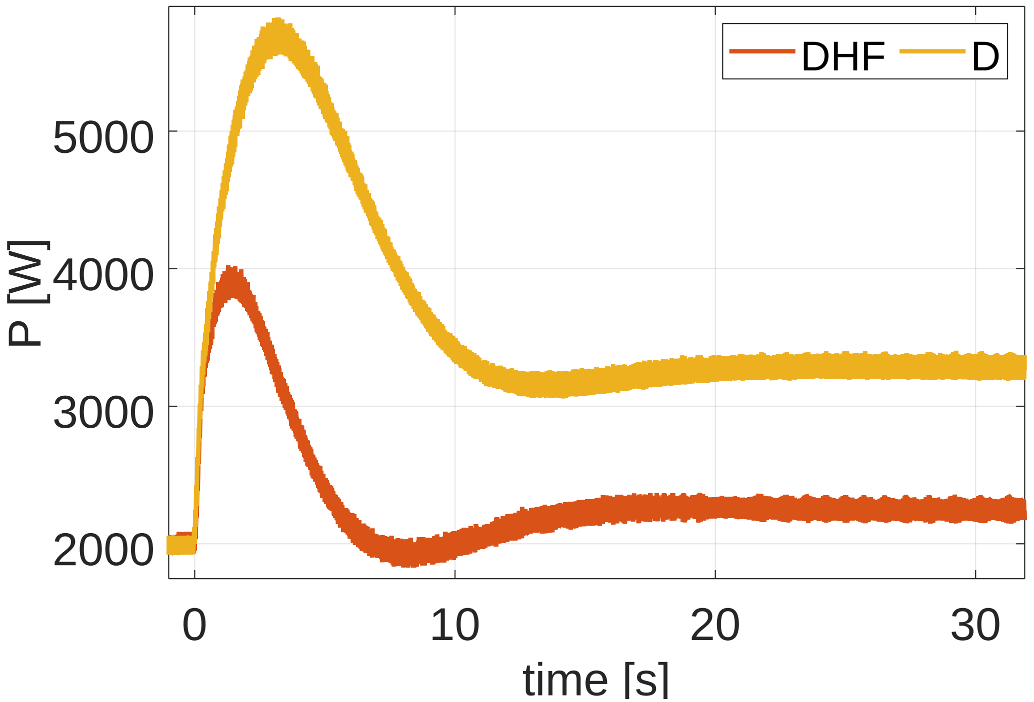
Emulating a real frequency drop (s)

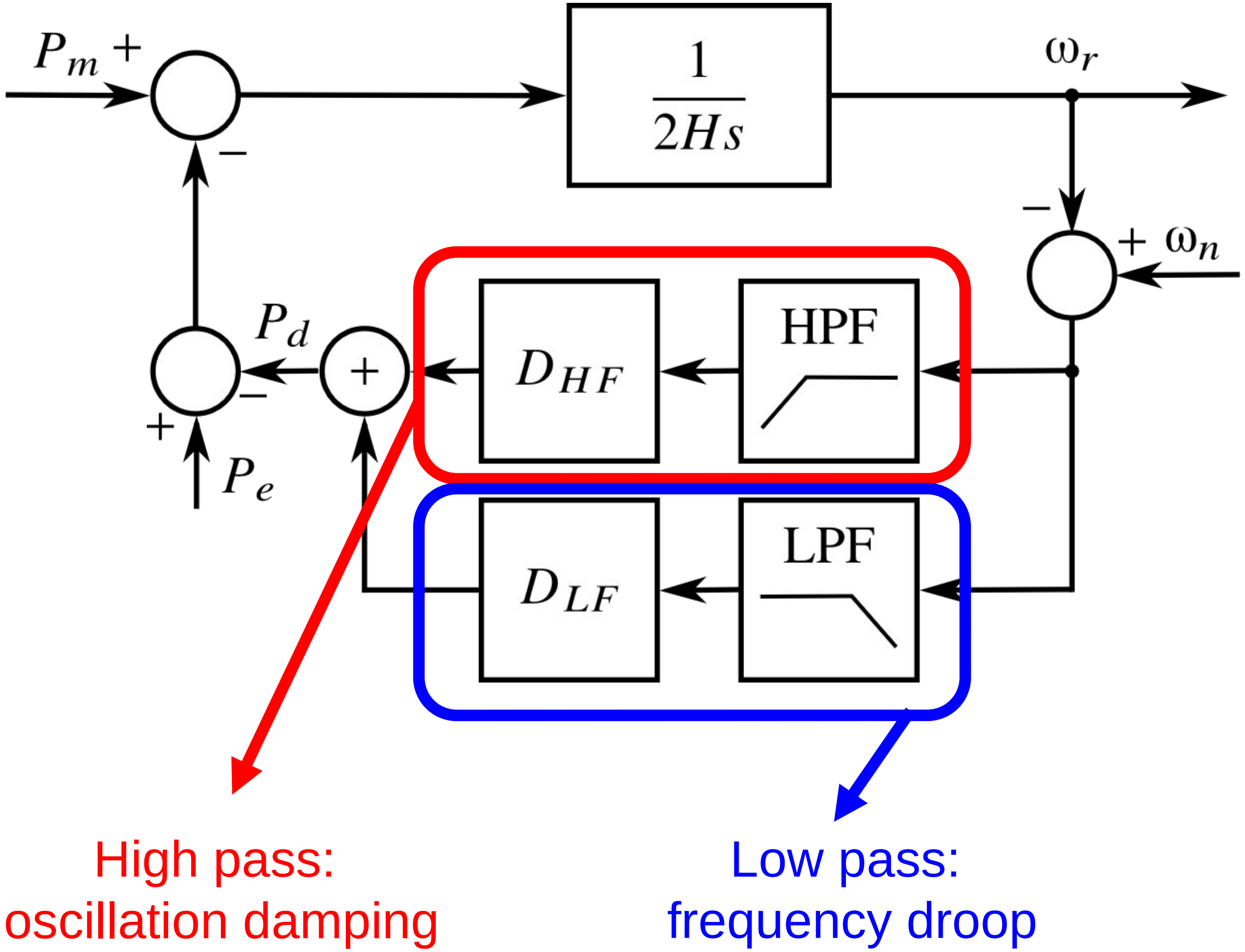


No power if frequency is constant

Alternative damping solution:

- High-pass + low-pass filters

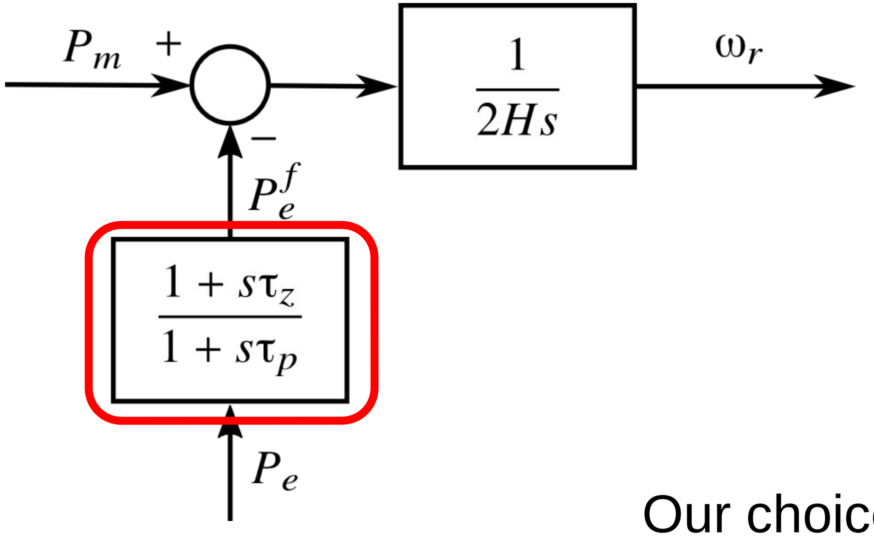




Splitting the frequency droop into high and low frequency channels

The high frequency (HF) channel is for damping,

the low frequency (less gain) for primary support.



Alternative damping solution:

- **Lead-lag filter** damping
- **Avoids coupling** with **frequency droop**
- Lower sensitivity to high frequency compared to PLL- or PI-damping

Our choice: