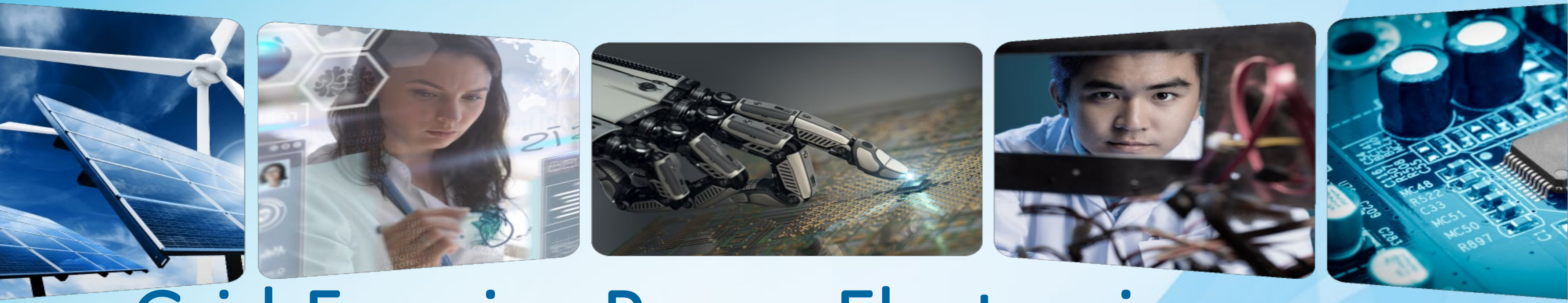


Grid-Forming Power Electronics Systems: Control Implementation and Stability Challenges

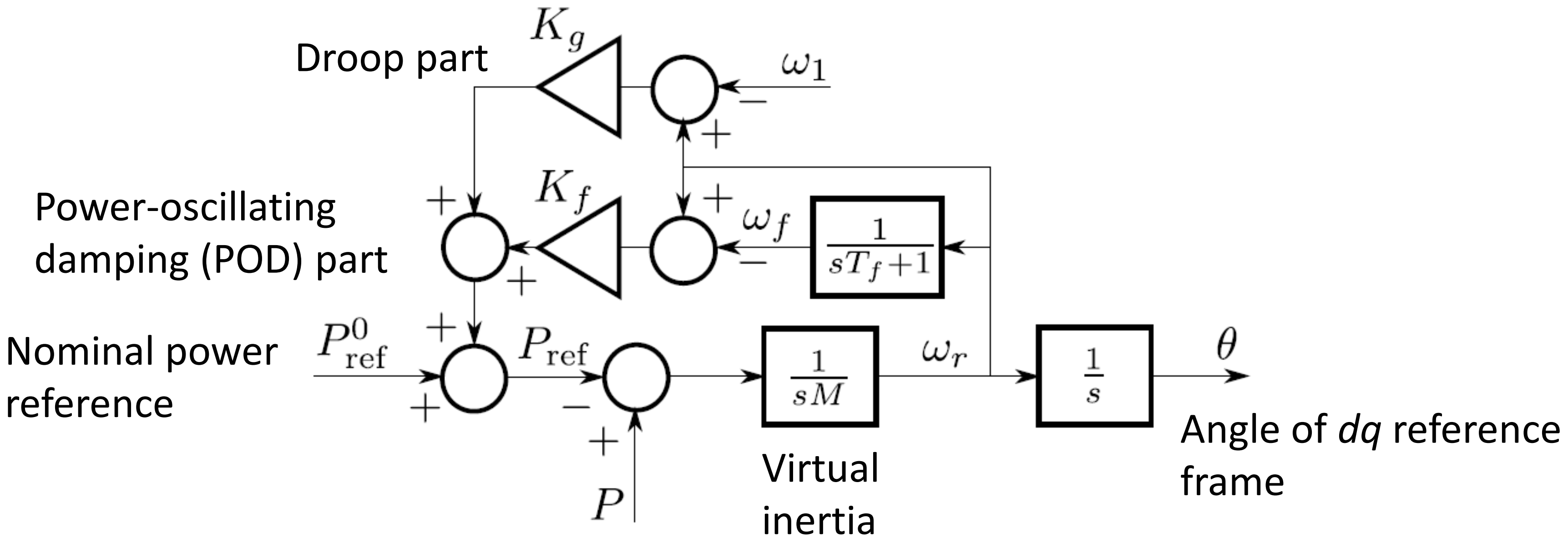
Lennart Harnefors, ABB, Corporate Research, Sweden

Virtual synchronous machine (VSM)

Objectives – all related to grid forming

- Provide virtual inertia
- Provide droop (primary) frequency control
- Enable operation of both grid-connected and islanded configurations without the need to change the control structure
- Improve the stability properties for connection to a weak grid by removing the phase-locked loop (PLL)
- Improve the weak-grid stability properties, as well as the over-all voltage stability of the grid, by using a voltage-stiff type of control

Basis for VSM: emulated swing equation



How form the converter-voltage reference based on the emulated swing equation?

Variants suggested in the literature

- **VISMA** - VSM principle according to Beck & Hesse
- **PSC** - Power-synchronization control according to Zhang, Harnefors & Nee
- **Synchronverter** - Special case of PSC according to Zhong & Weiss
- ***df/dt*** - Emulated swing equation reversed, supplying references to a vector current controller (VCC)

A closer look at *df/dt*

Step 1: Rearrange the swing equation as

$$P = P_{\text{ref}}^{0} + K_g(\omega_r - \omega_1) + K_f(\omega_r - \omega_f) + M\frac{d\omega_r}{dt}$$

Step 2: Substitute *P* by the power reference to the VCC and augment the derivative term by a low-pass filter

$$P_{\text{ref}}^{\text{cc}} = P_{\text{ref}}^{0} + K_g(\omega_r - \omega_1) + K_f(\omega_r - \omega_f) + M\frac{s}{sT_{\text{df}} + 1}\omega_r$$

Problem: Filter time constant often needs to be in the second range to preserve stability => counteracts virtual inertia

A closer look at VISMA

- Swing equation and other machine emulations feed references to VCC
- VCC known to have stability problems for connection to very weak grids => ditto for VISMA (and for *df/dt*). Requires robustness to maintain stability

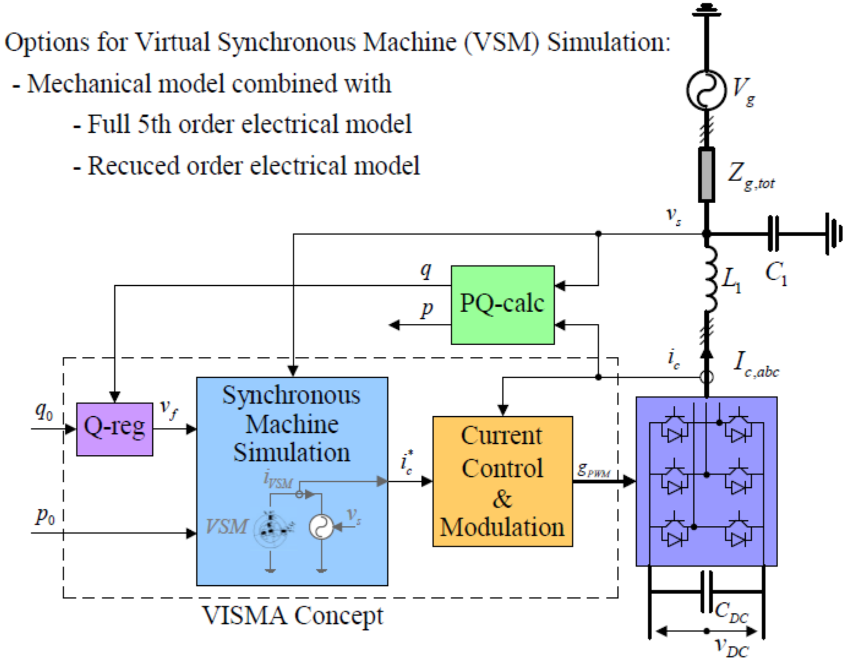
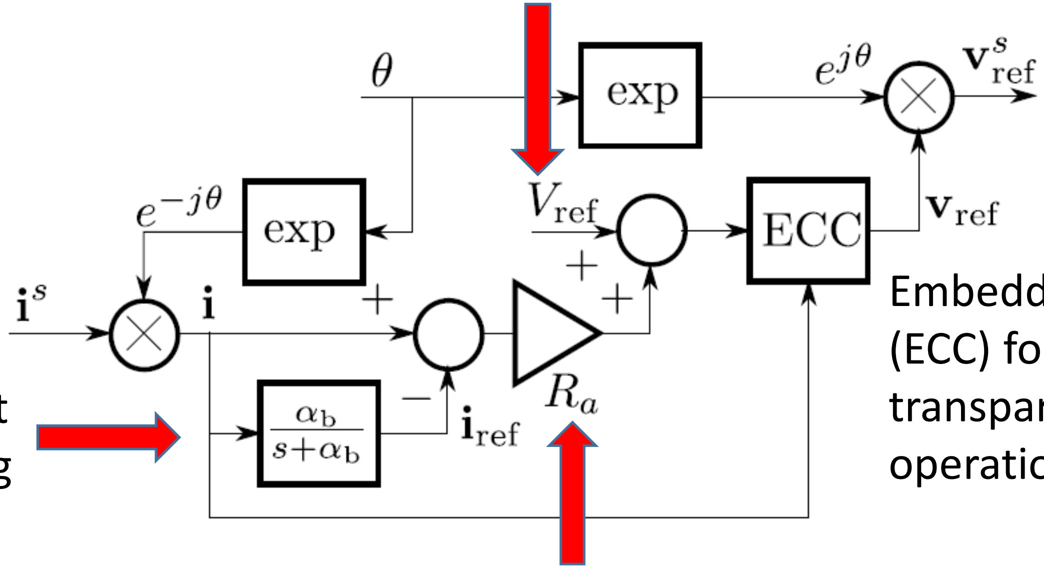


Fig. 2. VSM implementation providing current references for based on the VISMA concept proposed in [11]

Source: D'Arco & Suul: Virtual Synchronous Machines – Classification …

A closer look at PSC

Voltage stiff with the addition of …



Current reference set as a low-pass filtering of the actual current

Embedded current controller (ECC) for current limitation, transparent during normal operation (ABB patent)

… an ”active resistance” term for fundamental-frequency resonance damping

Synchronverter lacks ”active resistance” and ECC

To sum up

	Virtual inertia	Islanded operation	PLL less	Voltage stiff	Weak grid stable	Current controller
VISMA	Yes	Yes	Yes	No	If robust	Explicit
PSC	Optional	Yes	Yes	Yes	Yes	Embedded
Synchronverter	Yes	Yes	Optional	Yes	Possibly	No
df/dt	Yes	No	No	No	If robust	Explicit

PSC seems as a good choice, but how select the parameters?

Robust Analytic Design of Power-Synchronization Control

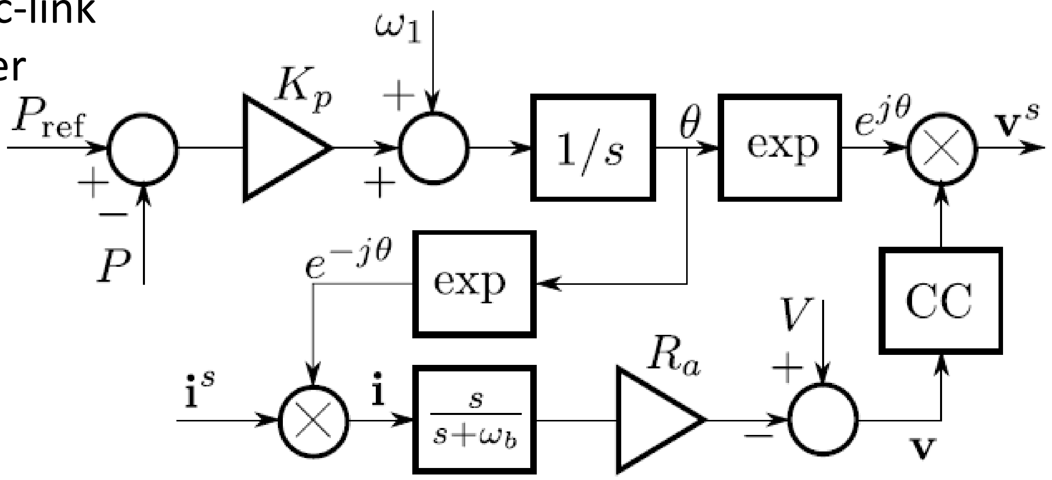
Lennart Harnefors, *Fellow, IEEE*, Marko Hinkkanen, *Senior Member, IEEE*, Usama Riaz, F. M. Mahafugur Rahman, and Lidong Zhang, *Senior Member, IEEE*

Empiric findings:

- Filter bandwidth α_b: 0.1 – 0.2 p.u.
- “Active resistance” R_a: 0.2 p.u.

VSM0H design with cascaded dc-link control

Set by dc-link controller



$$K_p = \frac{\omega_1 R_a}{\kappa V^2}$$

Novel analytic design recommendation, gives robust performance of both loops

Alternative: VSM design (compared in the sequel)

$$K_p = \frac{1}{K_g} = \frac{\sigma\omega_1}{S_{\text{base}}}$$

Examples, VSM0H

Satisfactory performance in all cases, except …

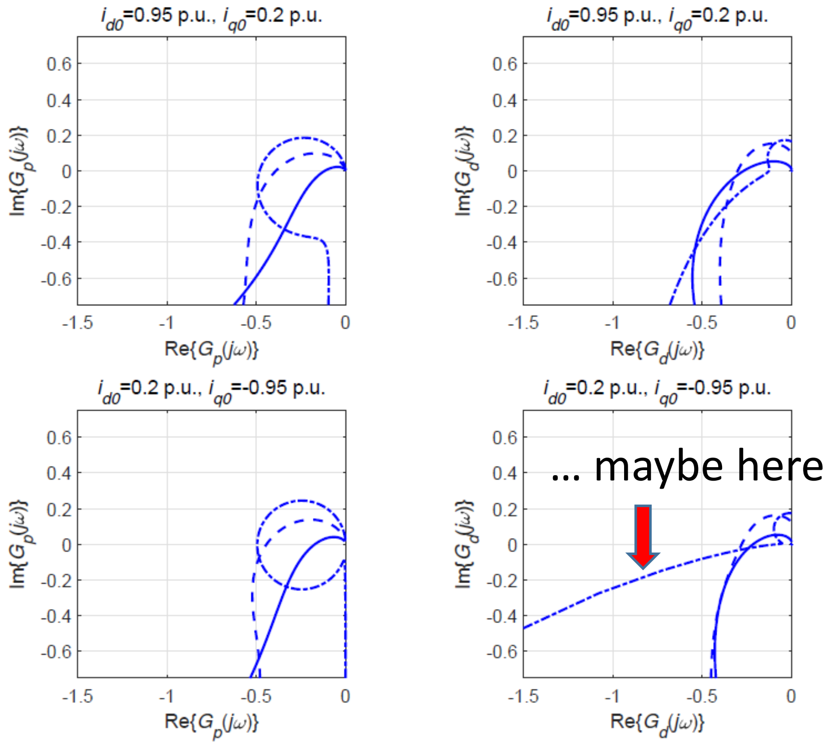


Fig. 5. Nyquist diagrams for (solid) SCR = 10, (dashed) SCR = 3, and (dashed-dotted) SCR = 1.

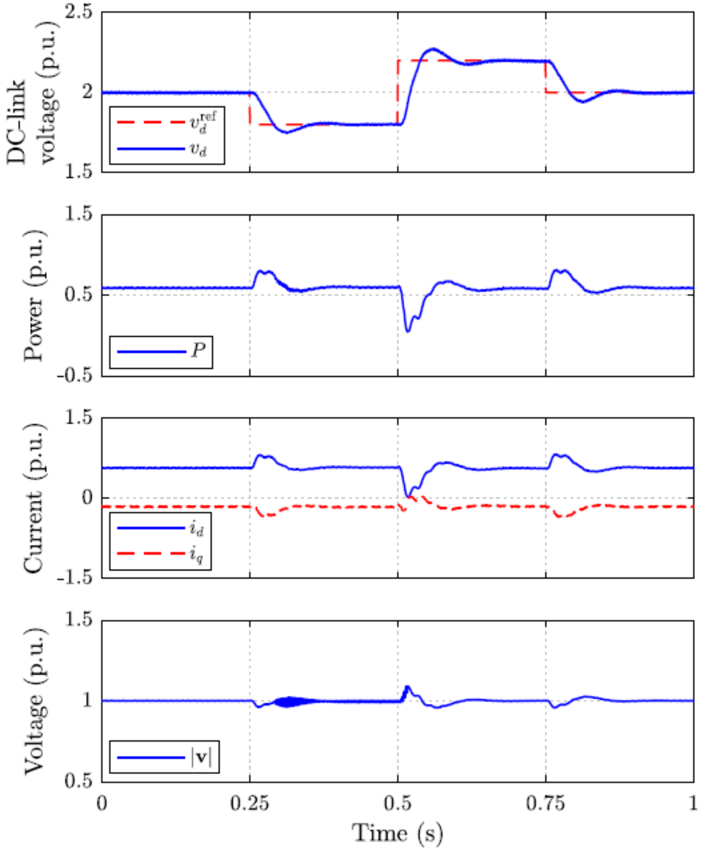


Fig. 15. Cascaded dc-link and active-power control for SCR = 1.

Examples, cont.

VSM design with *H*>0 gives adequate robustness of the power-control loop if POD is used …

VSM0H with 5% droop gives excellent robustness of the power-control loop …

… but not of the dc-link control loop!

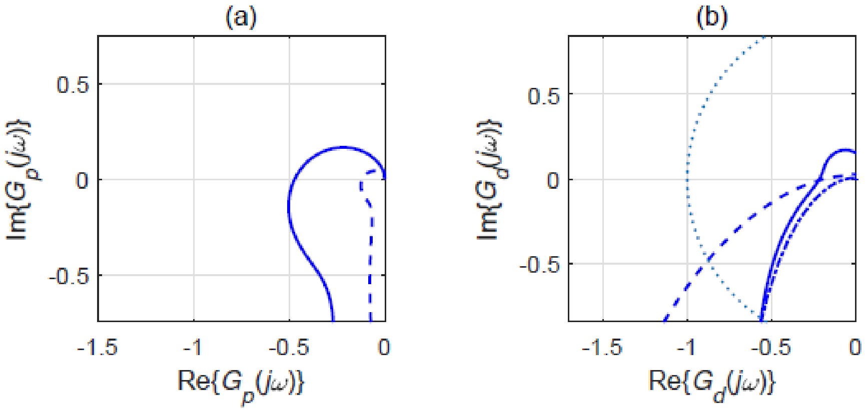


Fig. 7. Nyquist curves for (solid) the proposed design (13) and (dashed) VSM design (31), in both cases with K_d selected as (25). The dashed-dotted curve shows VSM design with K_d selected as 30% of (25).

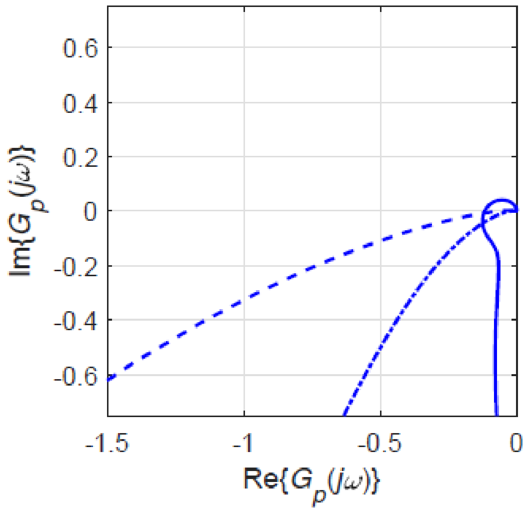


Fig. 8. Nyquist curves for VSM design with (solid) $H = K_D = 0$, (dashed) $H = 5$ s and $K_D = 0$, and (dashed-dotted) $H = 5$ s, $K_D = 50$ p.u., and $\alpha_f = 1$ rad/s.

… but don't even think of cascading dc-link control!

Conclusions

- Voltage-stiff control (PSC, Synchronverter) improves performance with very weak grids
- ”Active resistance” needed for resonance damping improvement (PSC)
- Embedded current controller needed for current limitation during faults and perhaps other transients (PSC)
- PSC-VSM0H can be robustly designed to allow cascaded dc-link control
- VSM0H design with standard droop ($\approx 5\%$) hampers cascaded dc-link control
- VSM design with *H*>0 requires POD for good damping, but does not allow cascaded dc-link control (even if possible it would counteract the virtual inertia)
- *df/dt* may require filtering with large time constant to maintain stability
- VISMA and *df/dt* require robust VCC for stability with very weak grids