CRESYM joint Harmony-BiGER workshop

TU Delft, June 5-6, 2023

A four-VSC benchmark system :

modelling, simulation and limits of phasor approximation

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Motivation and objectives

- Power-electronics converters push the phasor approximation to its limit (and beyond…)
- There is a need for benchmark systems
  - with large penetration of converters
  - small enough to be easily tractable
  - complex enough to reflect real-life systems
  - easily implemented in various simulation tools
- A 100% power electronics, 4-VSC test system is presented
- The embedded EMT models of VSCs were developed, tuned and thoroughly tested by Prof. Xavier Guillaud and his team at Ecole Centrale de Lille, France
  - this presentation focuses on models under the phasor (or “RMS”) approximation
  - simulation results in phasor-mode are compared with their EMT counterparts

Motivation and objectives

- Models and data of the benchmark are readily available in open source
- This is *not* a presentation about the “best” design and/or tuning of VSC controls
  - the models in this presentation are generic
  - they encompass many variants proposed in the literature

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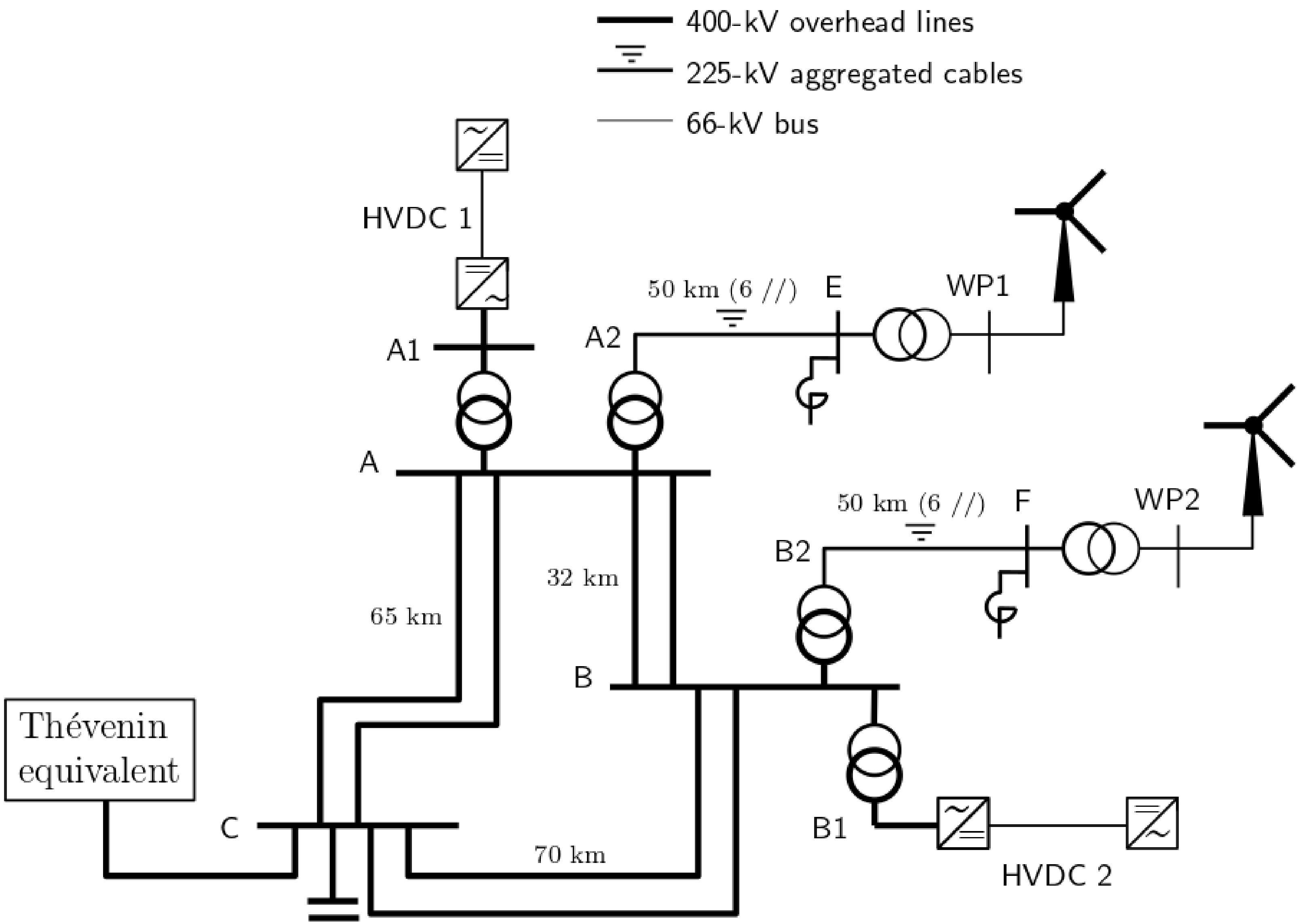
Topology and main characteristics



Network parameters

line / cable	nominal voltage	R (Ω)	X (Ω)	ωC/2 (μS)	length (km)	Snom (MVA)
A-C *	400	1.04	20.80	98	65	3000
A-B *	400	0.51	10.24	48	32	3000
B-C *	400	1.12	22.40	105	70	3000
A2-E **	225	0.42	0.83	9000	50 km	2400
B2-F **	225	0.42	0.83	9000	50 km	2400

* data of a single circuit

** data of 6 cables in parallel (400 MVA each)

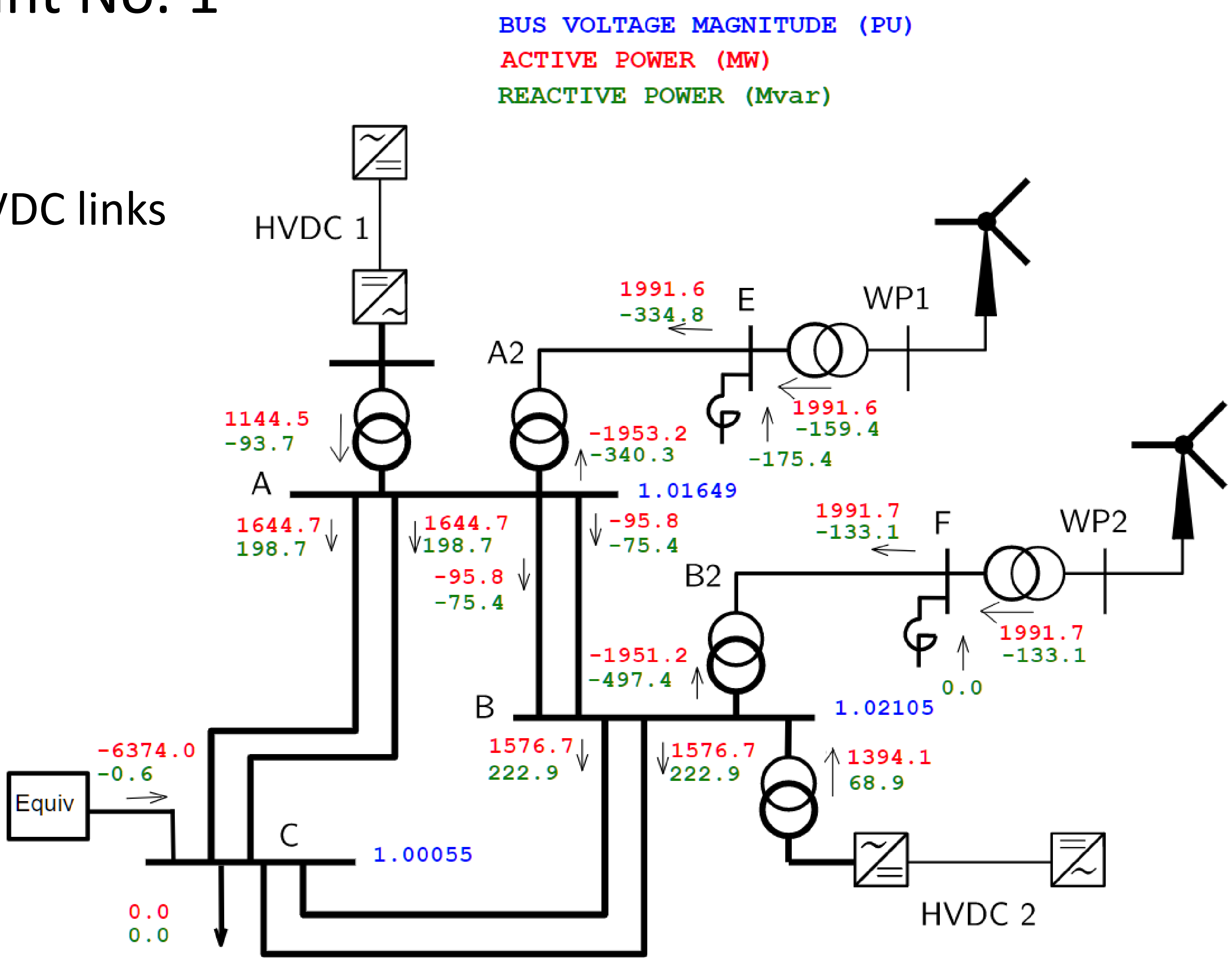
transformer	nominal voltages	R (%)	X (%)	transfo ratio (%)	Snom (MVA)
A1-A	320 / 400	0.5	15.0	102.	1200
B1-B	320 / 400	0.5	15.0	104.	1700
A2-A	225 / 400	0.5	15.0	102.	2400
B2-B	225 / 400	0.5	15.0	105.	2400
WP1-E *	66 / 225	0.5	12.0	105.	2400
WP2-F *	66 / 225	0.5	12.0	104.	2400

* 6 transformers in parallel, 400 MVA each

converter	Snom (MVA)	Pnom (MW)
WP1	2400	2300
WP2	2400	2300
HVDC1	1200	1150
HVDC2	1700	1630

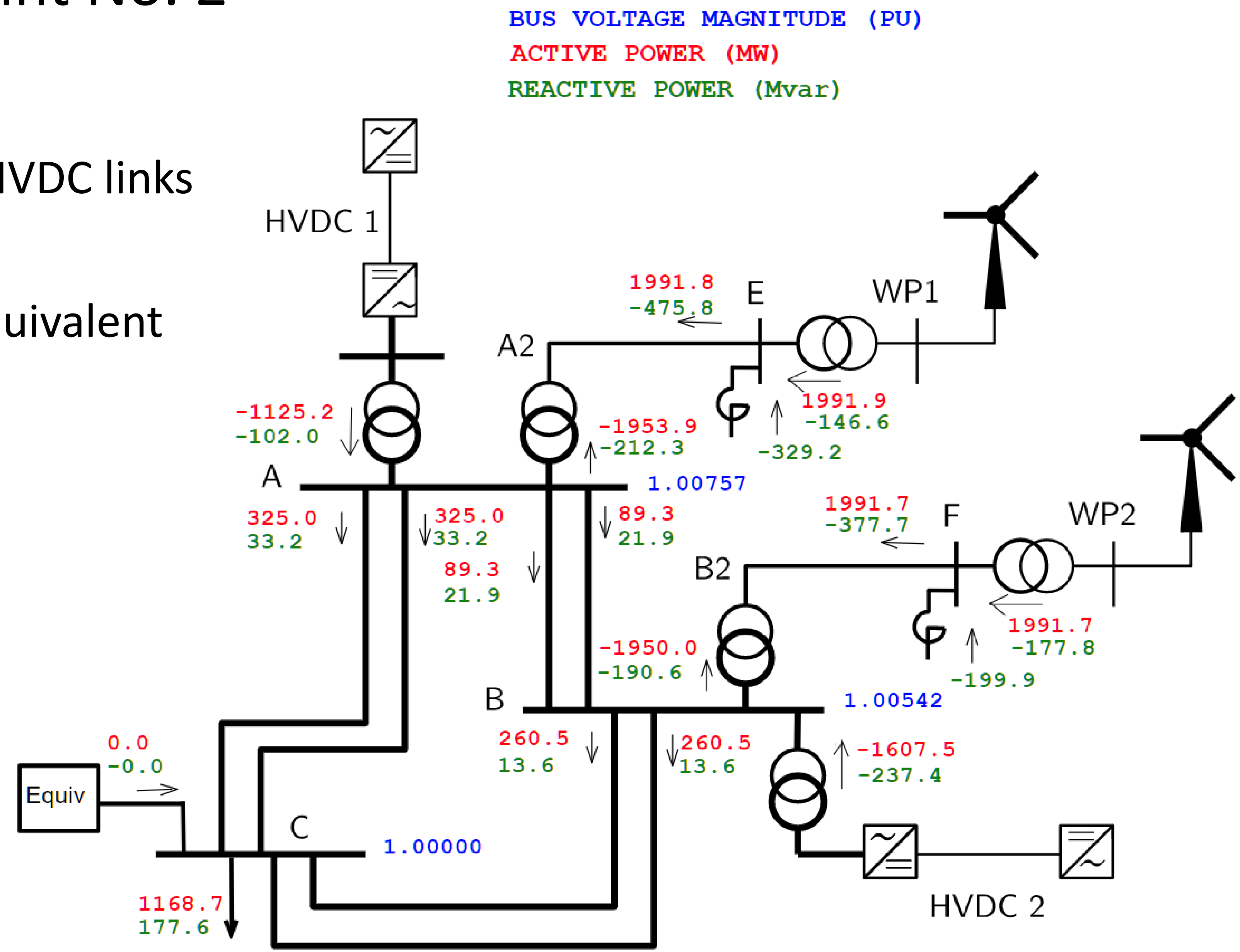
Operating point No. 1

- Power injected by WPs and HVDC links exported to external system
- network heavily loaded
- no load



Operating point No. 2

- WP productions exported by HVDC links
- load at bus C
- zero power flow in external equivalent
- network lightly loaded
- larger shunt reactors



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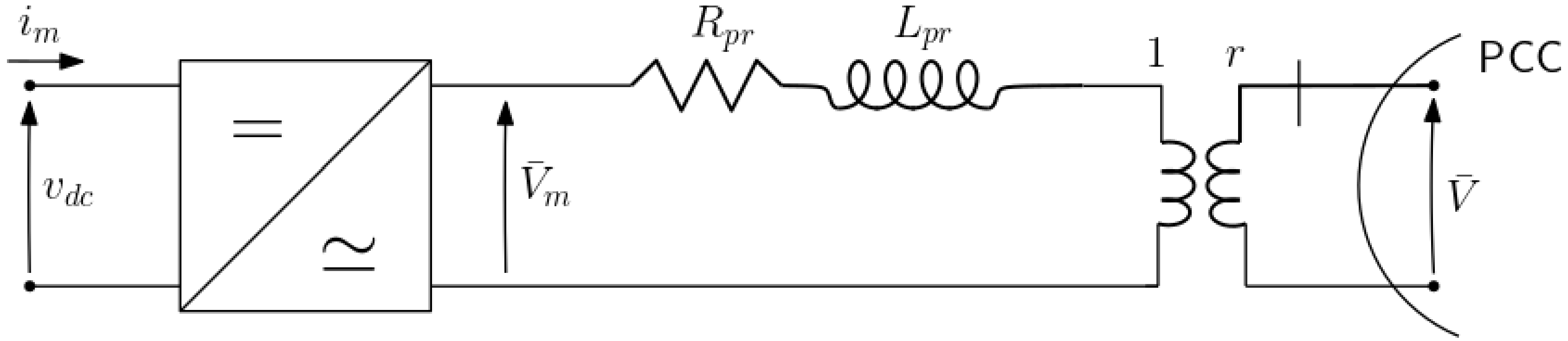
Grid-following converter



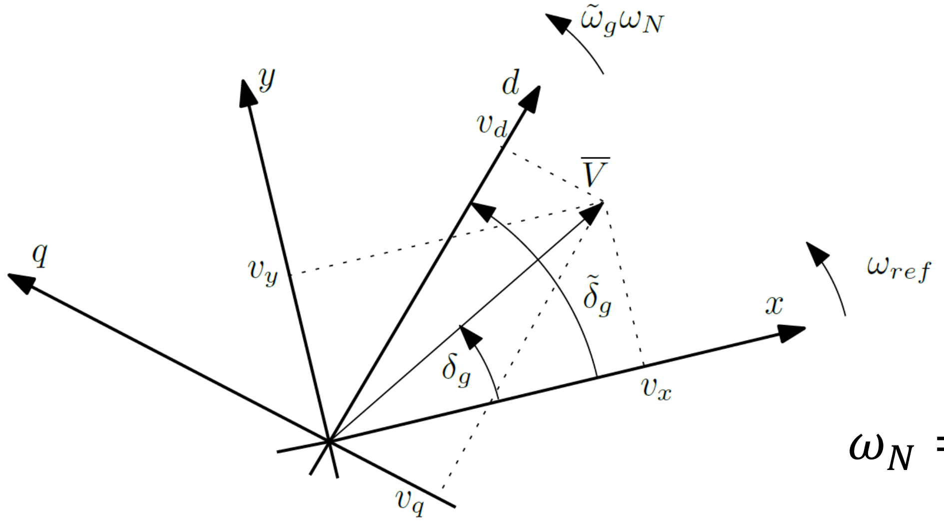
MMC-type converter connected to grid through transformer.

- no LC filter

DC side <u>not</u> modelled (v_{dc} assumed constant)

- focus is on AC grid dynamics

Grid-following converter : reference frames



$\omega_N = 2\,\pi\, f_N$: nominal angular frequency (in rad/s)

Network reference frame :

(x, y) axes rotating at angular speed ω_{ref} (rad/s)

v_x, v_y : rectangular components of PCC voltage phasor $\bar{V}$.

VSC control reference frame :

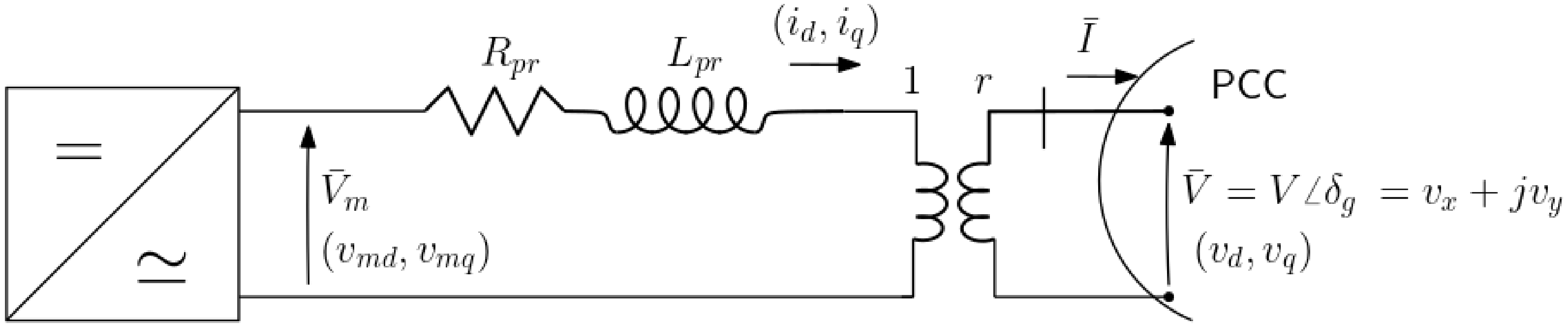
(d, q) axes tracking the voltage phasor and given by Phase Locked Loop

v_d, v_q : d, q components of $\overline{V}$

δ_g : phase angle of $\bar{V}$ wrt x (rad) $\tilde{\delta}_g$: angle between d and x (rad) in steady-state : $\tilde{\delta}_g = \delta_g$

$\widetilde{\omega}_g$: angular speed of (d, q) axes (pu/s)

Grid-following converter : voltages and currents in transformer



Passing from (x, y) to (d, q) reference frame :

voltage at PCC : $v_d = v_x \cos\tilde{\delta}_g + v_y \sin\tilde{\delta}_g$

$v_q = -v_x \sin\tilde{\delta}_g + v_y \cos\tilde{\delta}_g$

current in converter : $i_d = r\, i_x \cos\tilde{\delta}_g + r\, i_y \sin\tilde{\delta}_g$

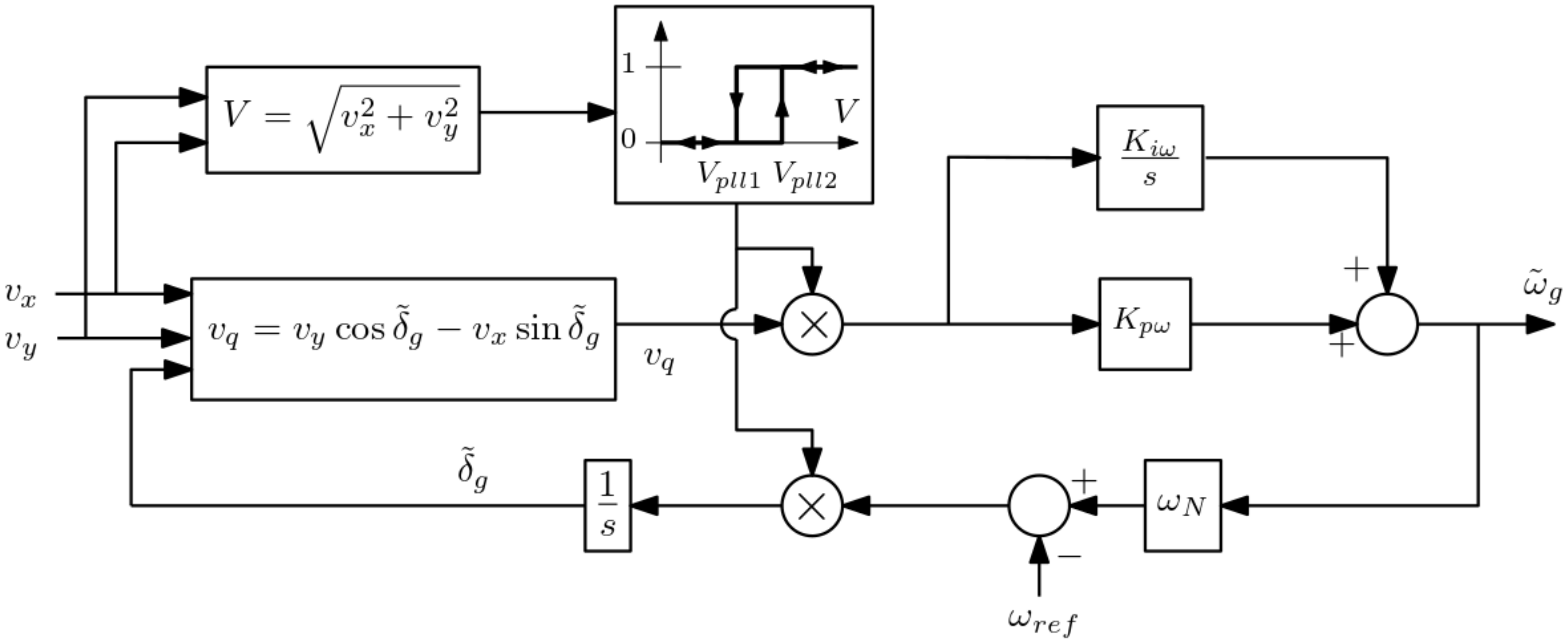
$i_q = -r\, i_x \sin\tilde{\delta}_g + r\, i_y \cos\tilde{\delta}_g$

Dynamics of current in transformer in (d, q) reference frame :

$$L_{pr}\frac{d}{dt}i_d = \omega_N \left(v_{md} - \frac{v_d}{r} - R_{pr}\, i_d + \tilde{\omega}_g\, L_{pr}\, i_q\right)$$
$$L_{pr}\frac{d}{dt}i_q = \omega_N \left(v_{mq} - \frac{v_q}{r} - R_{pr}\, i_q - \tilde{\omega}_g\, L_{pr}\, i_d\right)$$

- differential equations not in agreement with the phasor approximation of network (algebraic eqs.)
- aimed at (hopefully) capturing fast dynamics of converter

Grid-following converter : Phase Locked Loop (PLL)



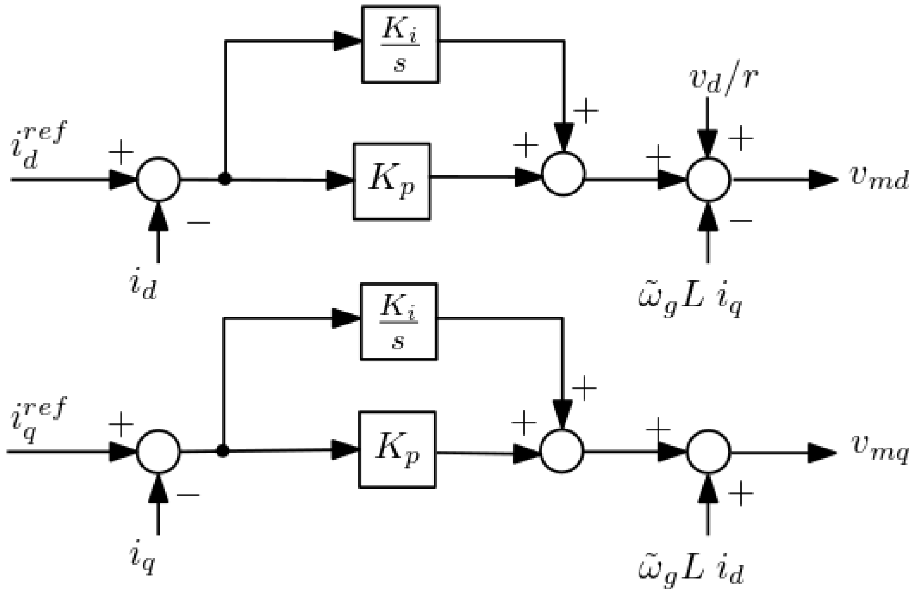
$$K_{p\omega} = \frac{10}{T_{pll}\ \omega_N} \qquad K_{i\omega} = \frac{25}{T_{pll}^2\ \omega_N} \qquad T_{pll} : 100 \text{ ms}$$

values in per unit on the S_{nom} base (nominal apparent power of converter)

Blocking/unblocking the PLL for low voltage :

V : PCC voltage magnitude (pu) V_{pll1}= 0.4 pu V_{pll2}= 0.5 pu

Grid-following converter : d-q current control



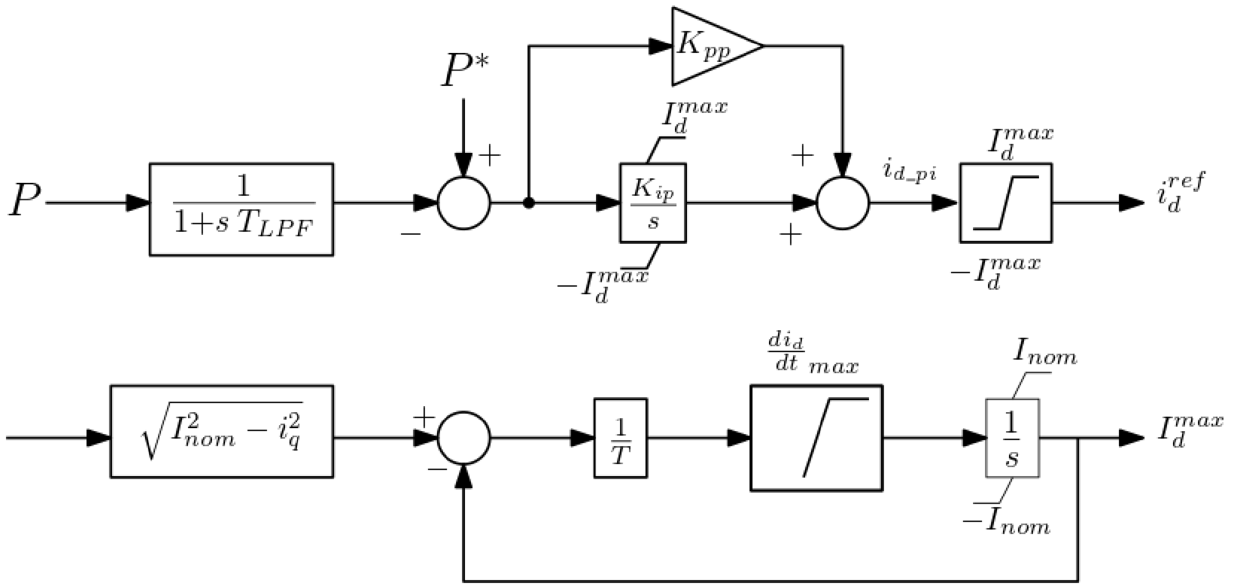
$K_i = R_{pr}\ \omega_c$ = 6 pu/s

$K_p = L_{pr} \frac{\omega_c}{\omega_N}$ = 0.4584 for WP1 and WP2

= 0.5730 for HVDC1 and HVDC2

(ω_c = 1200 rad/s)

Grid-following converter : active power control



$T_{LPF} = \frac{1}{\omega_{LPF}}$ = 1/300 = 3.3 ms $\quad$ K_{ip}= 10 pu/s $\quad$ $K_{pp} = K_{ip}/\,\omega_{LPF}$ = 10/300 = 33.3

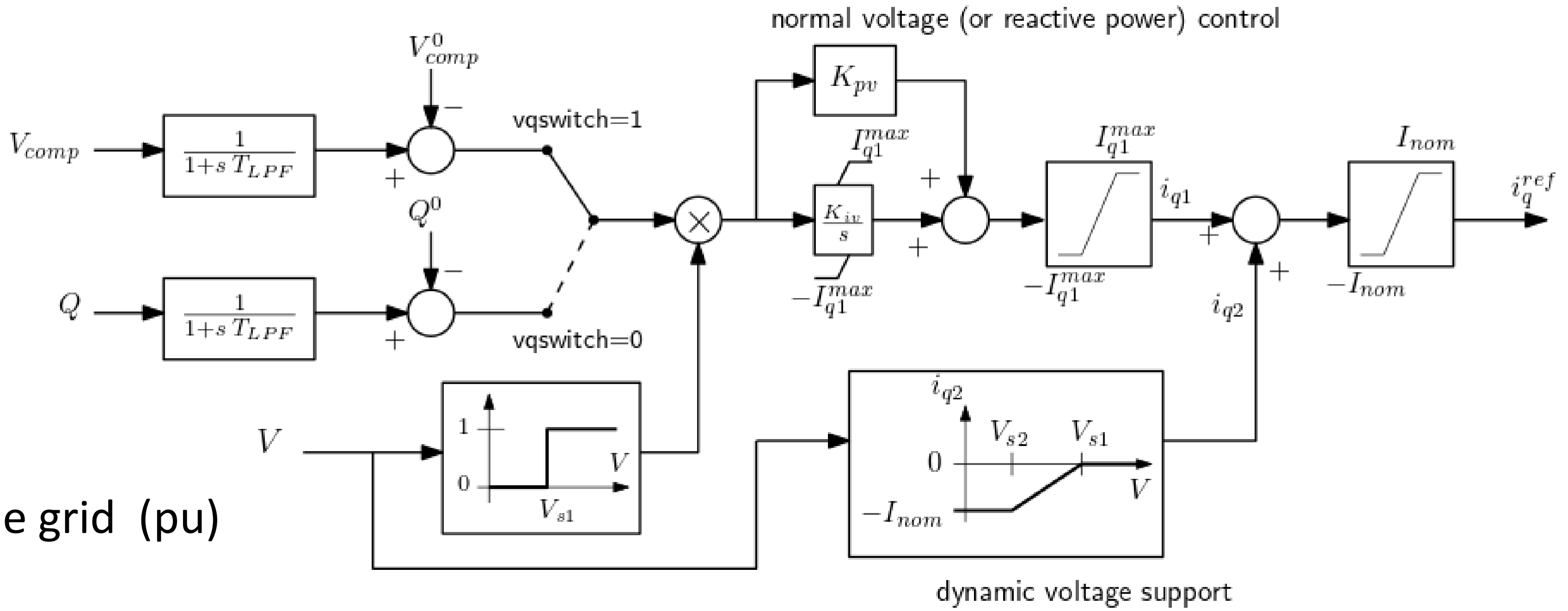
I_{nom} : nominal current (1 pu)

Lower block-diagram : limits the rate of recovery of I_d^{max} after it has been decreased by an increase of i_q (priority given to reactive current)

T : small time constant (0.002 s) $\quad$ $(\frac{di_d}{dt})_{max}$= 0.5 pu/s for WP1 and WP2

= 10 pu/s for HVD1 and HVDC2

Grid-following converter : voltage / reactive power control



Q : reactive power injected into the grid (pu)

T_{LPF}= 3.3 ms

V_{comp} : compensated voltage : $V_{comp} = |\frac{\bar{V}}{r} + (R_c + jX_c)\, r\, \bar{I}|$

I^{max}_{q1} : see next slide

$R_c = R_{pr}$ and $X_c = L_{pr}$ $\Rightarrow$ the V_m voltage magnitude is controlled

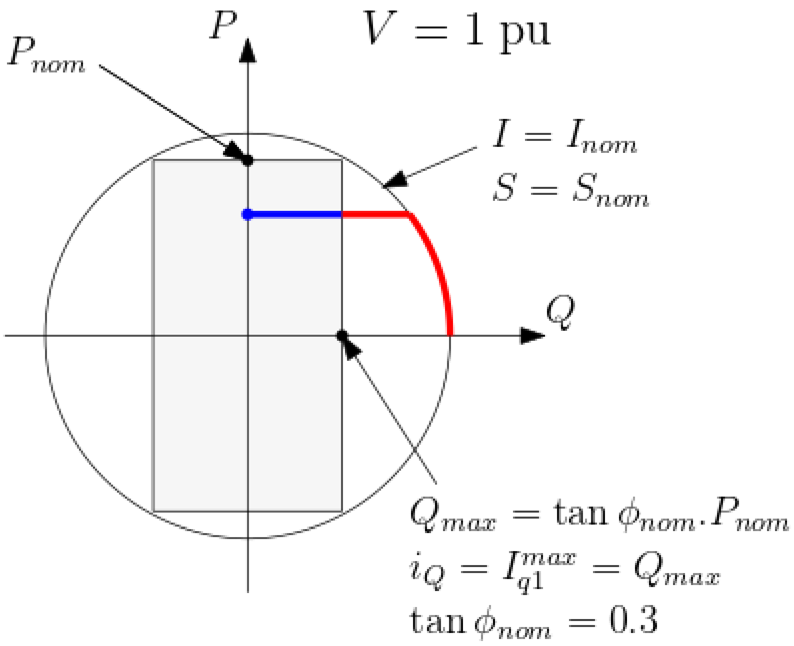
vqswitch =1 K_{iv}= 50 pu/s K_{pv}= K_{iv}/ω_{LPF}= 0.1667

vqswitch =0 K_{iv}= 10 pu/s K_{pv}= K_{iv}/ω_{LPF}= 0.0333

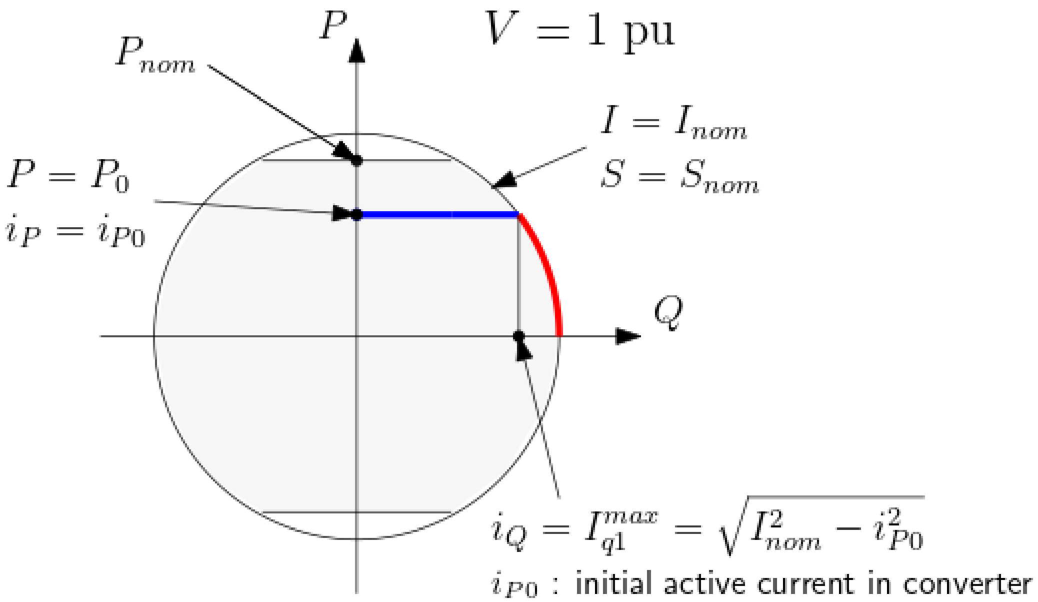
Dynamic voltage support : V_{s1} = 0.95 pu V_{s2} = 0.5 pu

Grid-following converter : limit I_{q1}^{max} on quadrature current

First option : limited capability



Second option : full capability

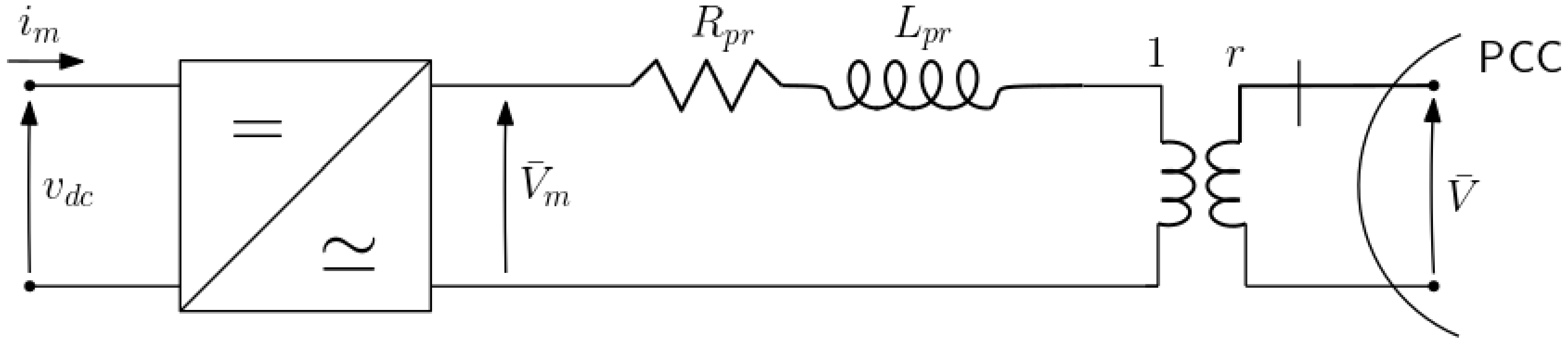


normal voltage control

dynamic voltage support

The second option has been selected

Grid-forming converter



MMC-type converter connected to grid through transformer.

- no LC filter

DC side <u>not</u> modelled (v_{dc} assumed constant)

- focus is on AC grid dynamics

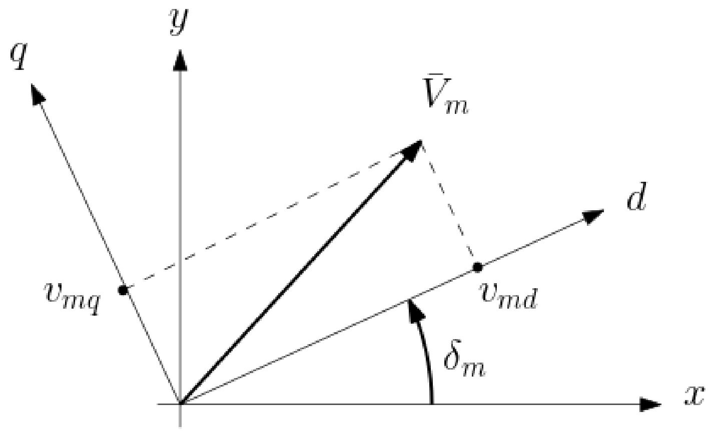
Grid-forming converter : reference frames and voltage control

The *d* axis is attached to the internal phase angle δ_m

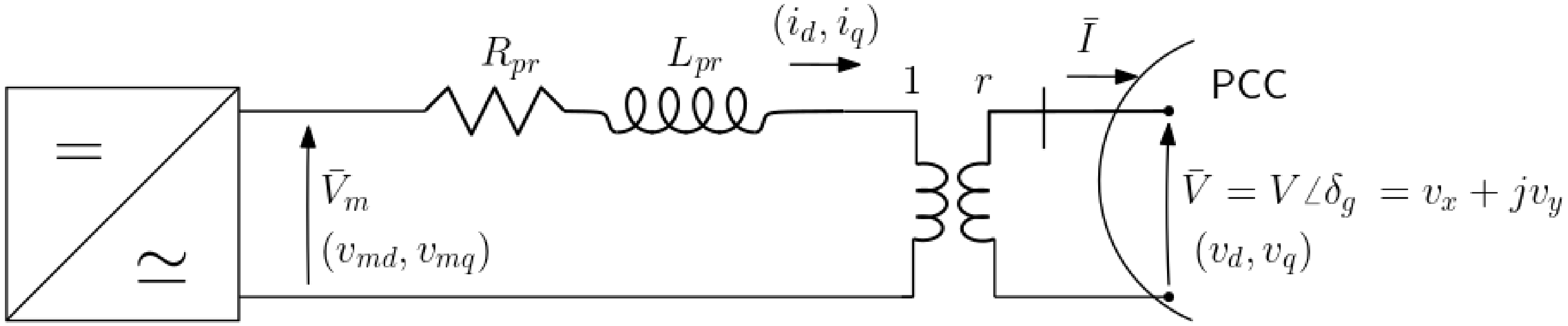
- δ_m is given by the active power and phase angle control : see slide 22

In normal operation, when the converter current is not limited :

- δ_m is the phase angle of the modulated voltage
- $\bar{V}_m$ lies along the *d* axis, i.e. $v_{mq} = 0$
- the magnitude of $\bar{V}_m$ is constant, i.e. $v_{md} = V_m^*$ (voltage setpoint)



Grid-forming converter : voltages and currents in transformer



Passing from (x, y) to (d, q) reference frame :

voltage at PCC : $v_d = v_x \cos\delta_m + v_y \sin\delta_m$

$v_q = -v_x \sin\delta_m + v_y \cos\delta_m$

current in converter : $i_d = r\, i_x \cos\delta_m + r\, i_y \sin\delta_m$

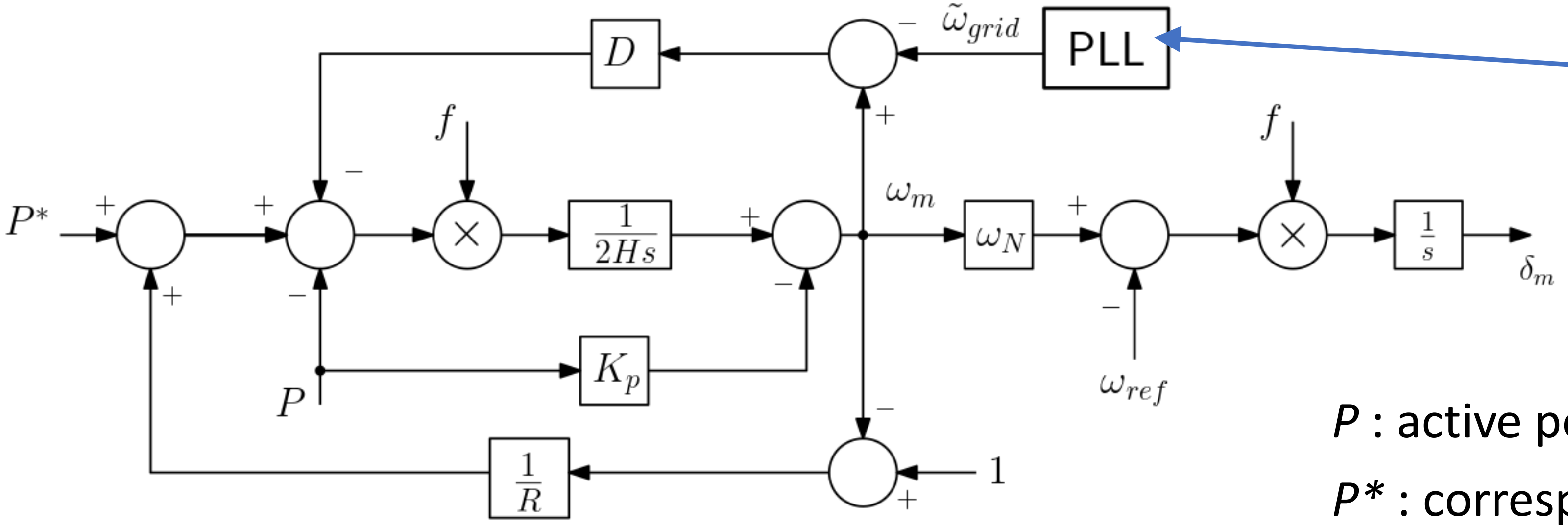
$i_q = -r\, i_x \sin\delta_m + r\, i_y \cos\delta_m$

Dynamics of current in transformer in (d, q) reference frame :

$$L_{pr}\frac{d}{dt}i_d = \omega_N \left(v_{md} - \frac{v_d}{r} - R_{pr}\, i_d + \tilde{\omega}_g\, L_{pr}\, i_q\right)$$
$$L_{pr}\frac{d}{dt}i_q = \omega_N \left(v_{mq} - \frac{v_q}{r} - R_{pr}\, i_q - \tilde{\omega}_g\, L_{pr}\, i_d\right)$$

- same remark as for the grid-following converter (differential, not algebraic eqs.)

Grid-forming converter : active power and phase angle control



same model as in grid-following scheme

T_{pll} = 50 ms

P : active power produced (pu)

P^* : corresponding setpoint (pu)

ω_m : converter angular frequency (pu)

f : freezing factor : see next slide

Inertia emulation : H= 5 s

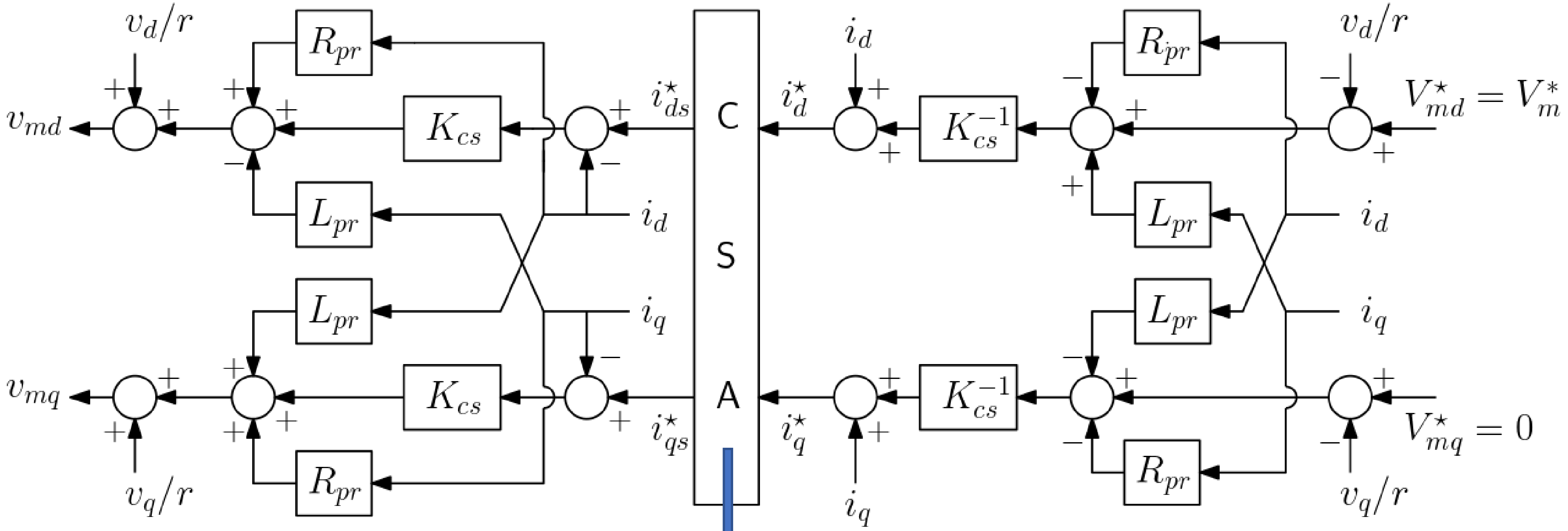
Damping : 2 options :

- with PLL to estimate grid frequency ($\tilde{\omega}_{grid}$) : D= 200 - 300 K_p= 0
- IP scheme without PLL : D= 0 K_p= 0.01592

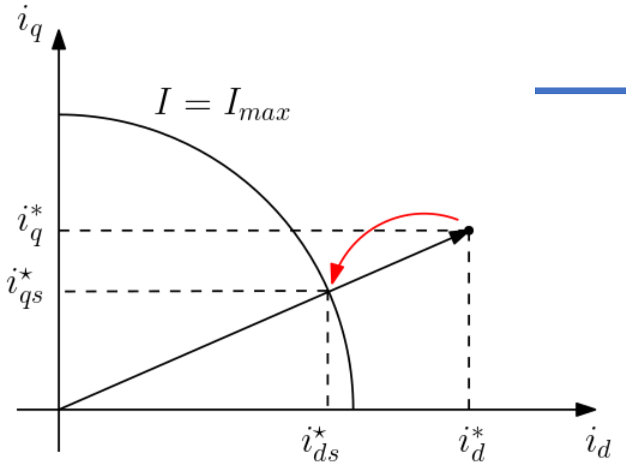
Both options are equivalent to a "Virtual Synchronous Machine" scheme

Participation to primary frequency control : droop R= 25

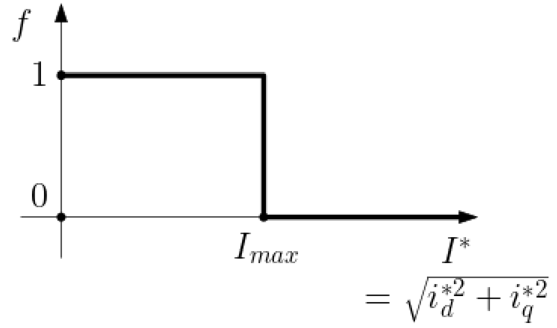
Grid-forming converter : current limiter



Current saturation :



Freezing factor f :



K_{cs} = 2.05 pu $\quad$ I_{max} = 1 pu

Check : when current not limited :

$$i_d^* = i_{ds}^* \qquad i_q^* = i_{qs}^*$$

$$v_{md} = V_{md}^* = V_m^* \qquad v_{mq} = V_{mq}^* = 0$$

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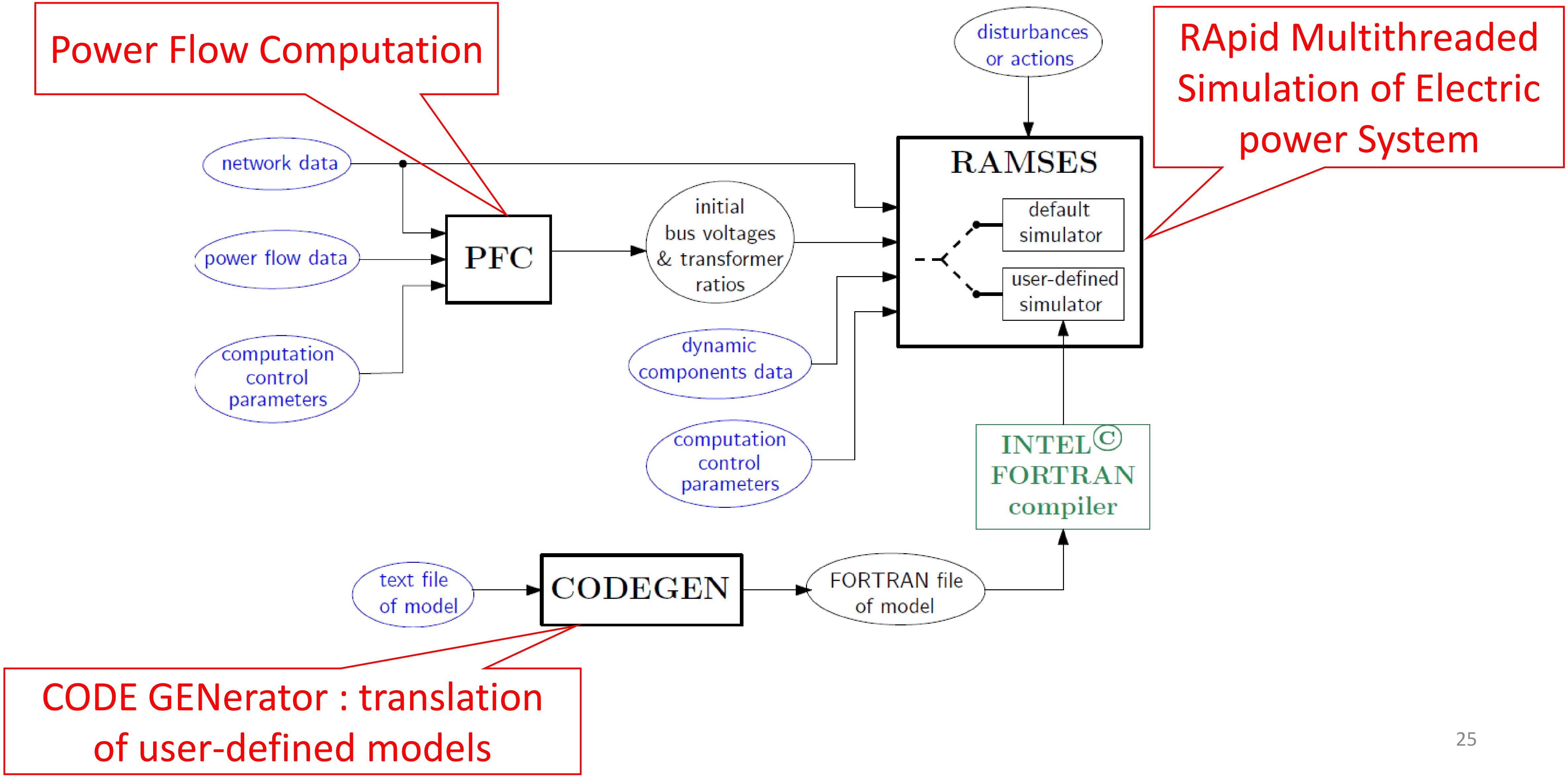
STEPSS

(**S**tatic and **T**ransient **E**lectric **P**ower **S**ystems **S**imulation)



STEPSS

(**S**tatic and **T**ransient **E**lectric **P**ower **S**ystems **S**imulation)

RAMSES

- differential/algebraic equations solver developed at the Univ. of Liège by P. Aristidou and T. Van Cutsem
- phasor approximation
- decomposition (Schur-complement) + localization techniques
- parallel processing

CODEGEN

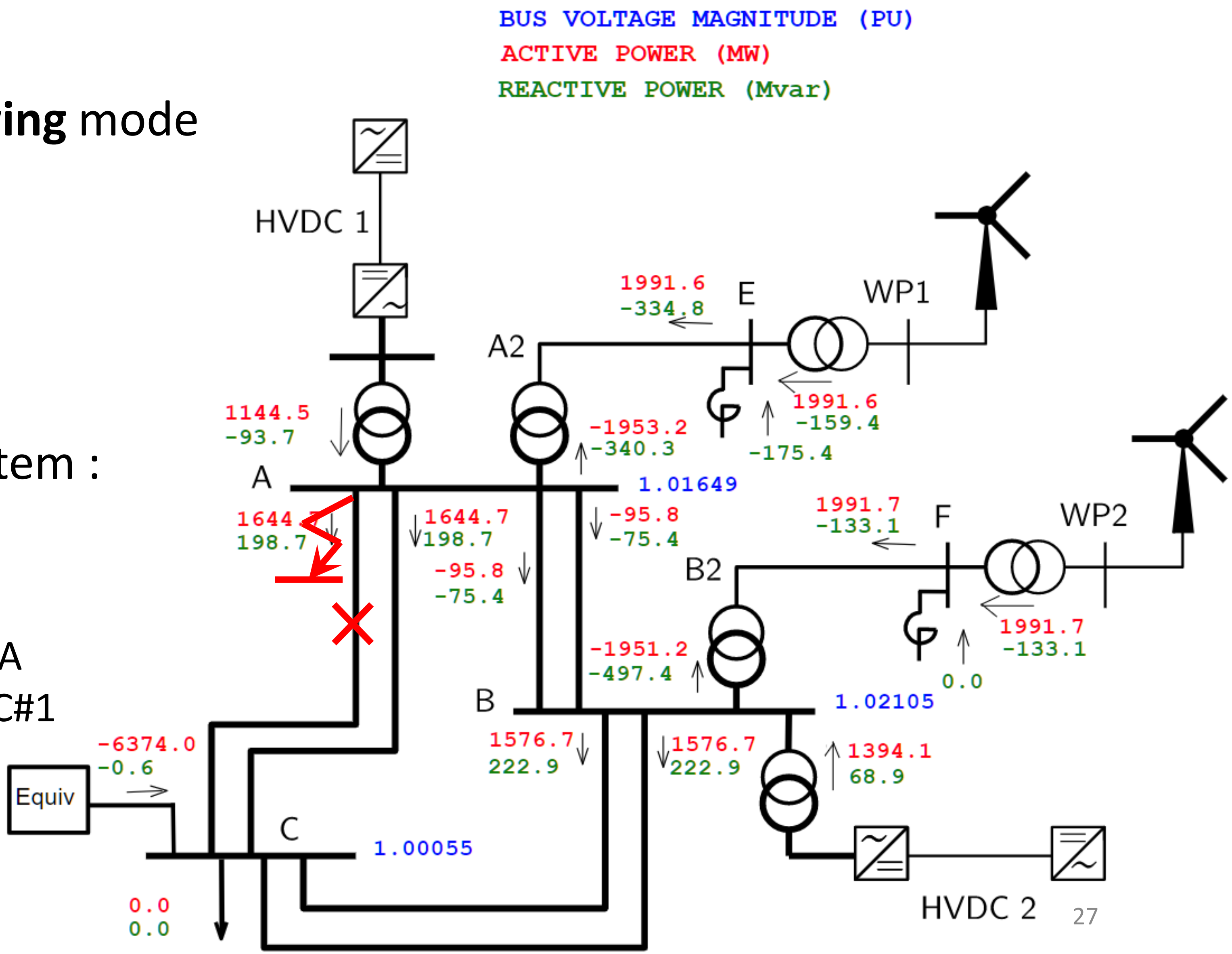
- receives user-defined models written according to a simple syntax
- translates them into FORTRAN 2003 code, to be compiled and linked to the rest of RAMSES
- 4 types of models : excitation control of sync. mach. / torque control of sync. mach. / injectors / two-ports
- models freely shared by users $\rightarrow$ **open-source** simulation software

LICENSE TERMS

STEPSS can be used free of charge for non-commercial/non-profit purposes, in a version limited to 1000 buses and 2 cores.

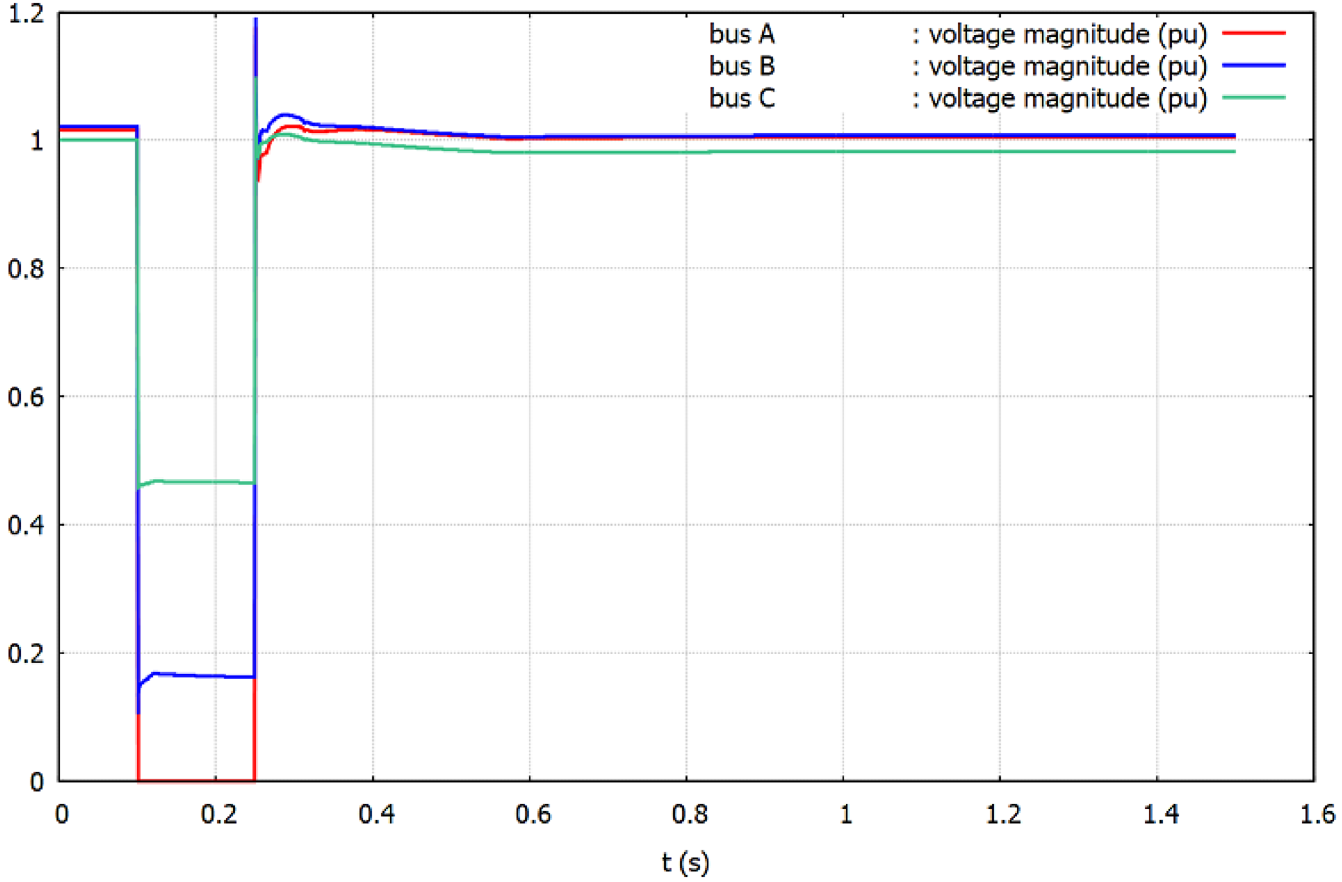
Example: large-disturbance simulation

- operating point No. 1
- WP1, WP2 & HVDC1 in grid-**following** mode
  - WP1 in reactive power control
  - WP2 and HVDC1 in voltage control
  - dynamic voltage support disabled
- HVDC2 in grid-**forming** mode
- short-circuit power of external system : 10 000 MVA
- disturbance :
  - solid fault on line A-C#1, next to bus A
  - cleared in 150 ms by opening line A-C#1



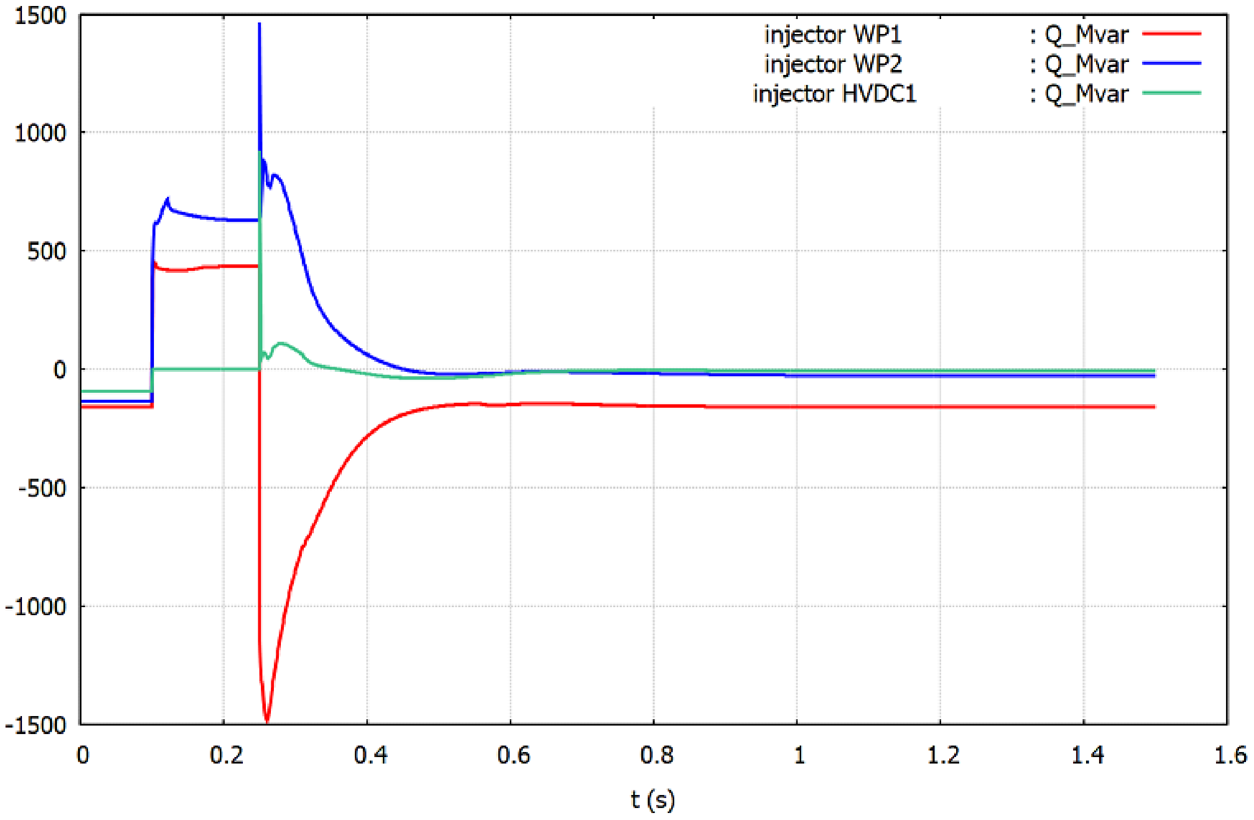
Example: large-disturbance simulation

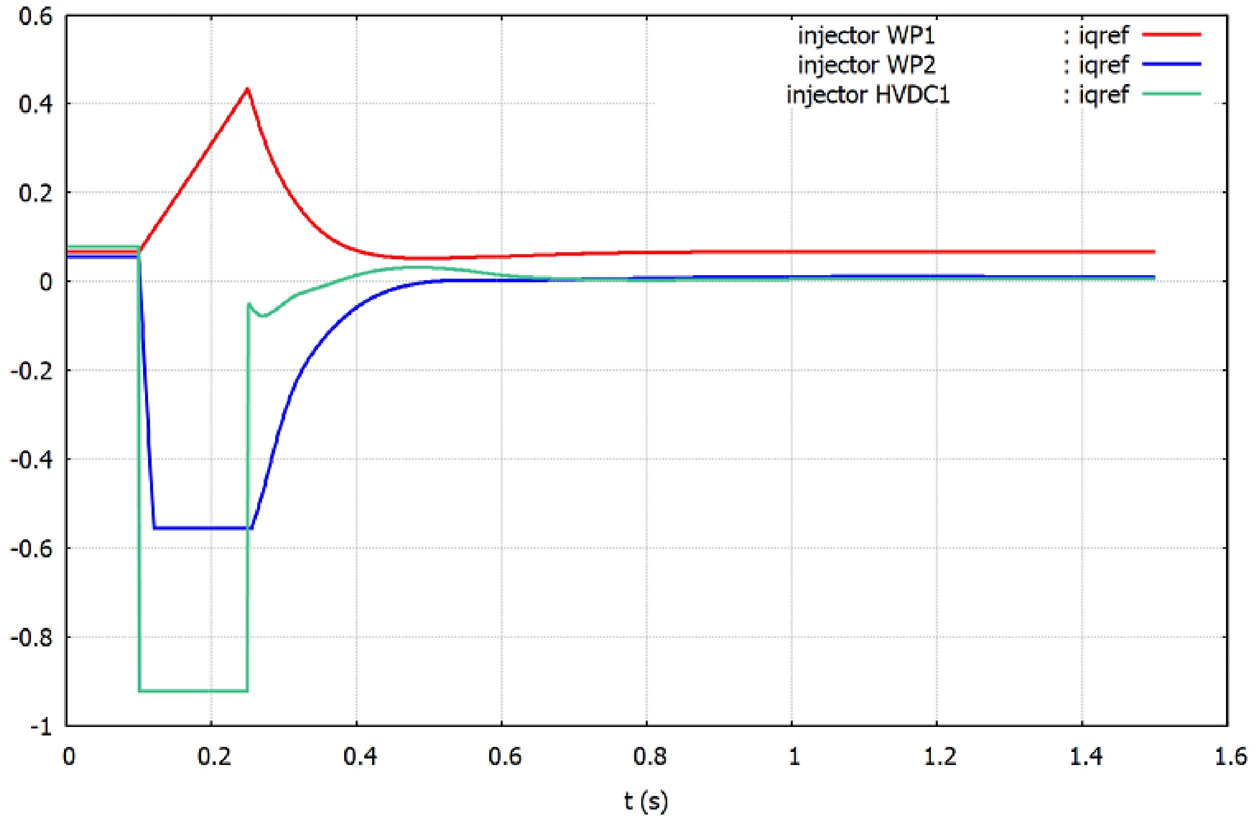
Network voltages



Example: large-disturbance simulation

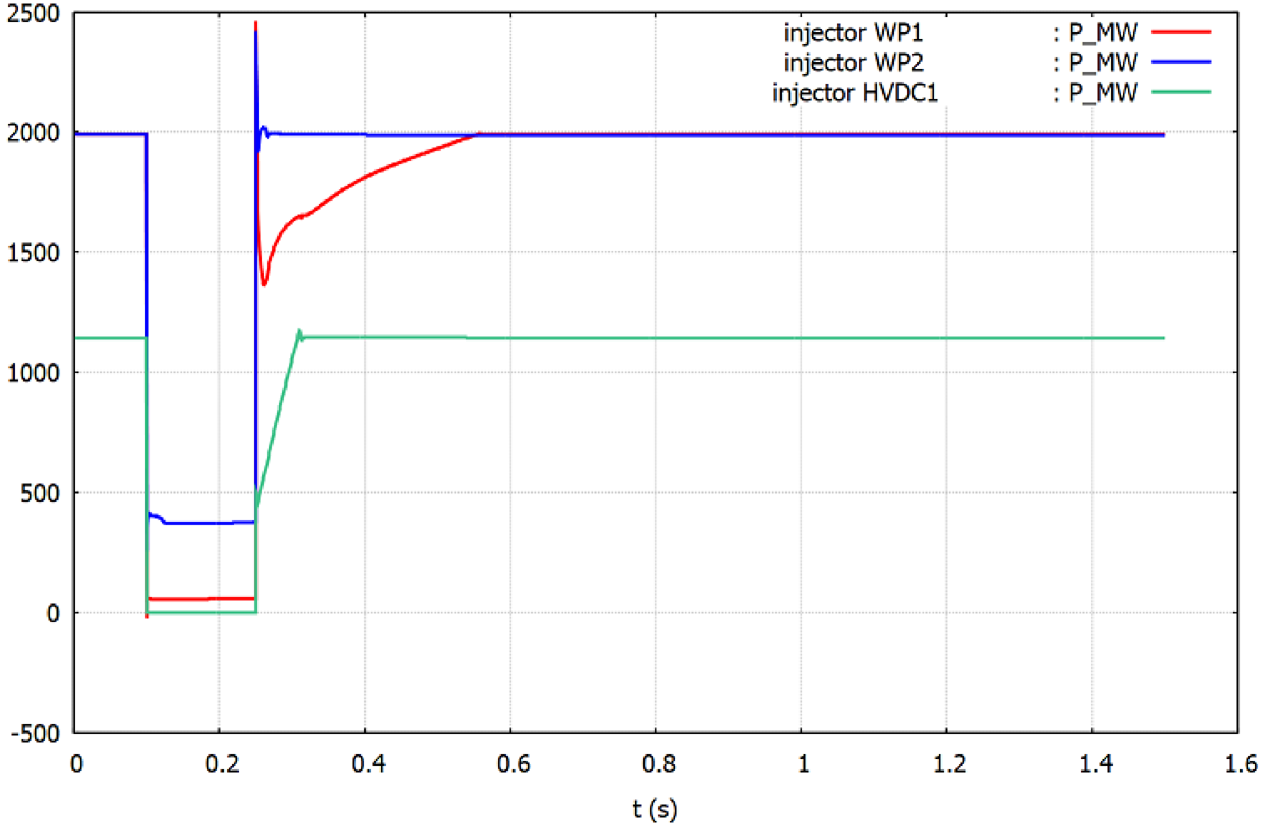
Responses of the converters in grid-following mode

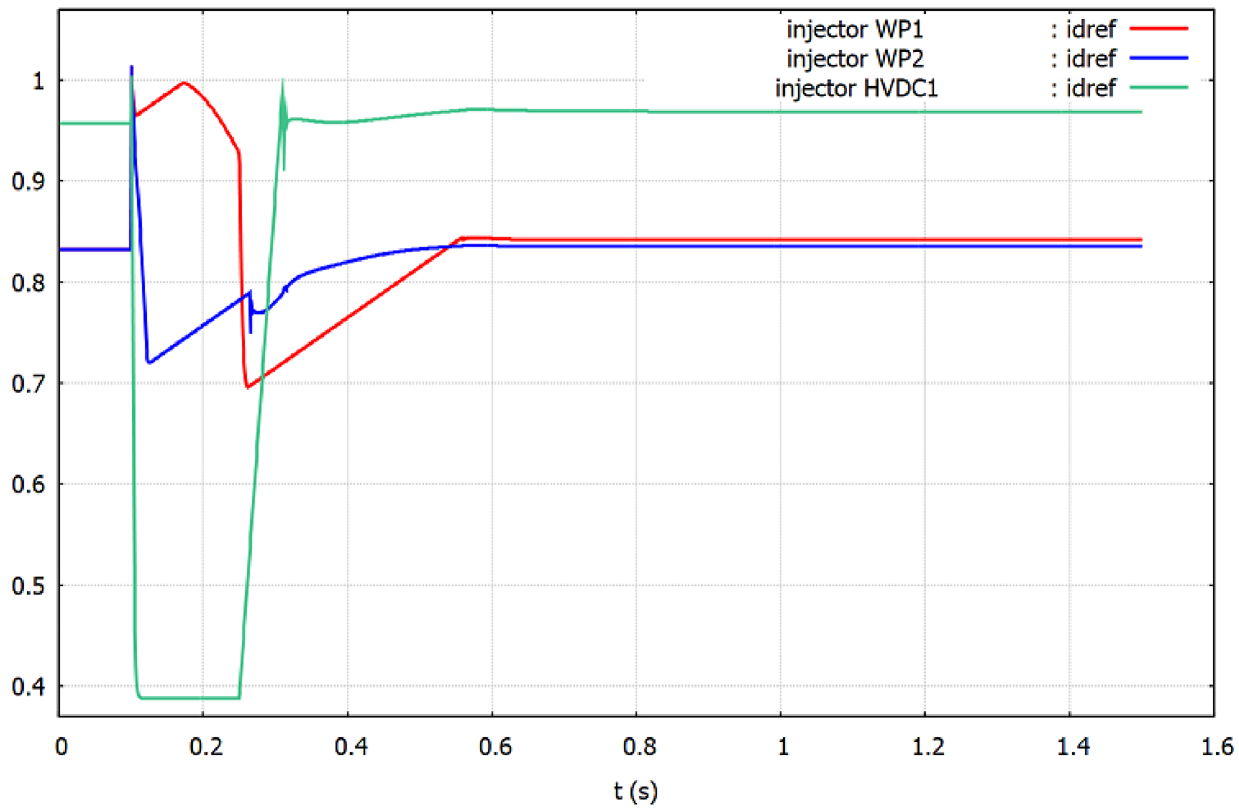




Example: large-disturbance simulation

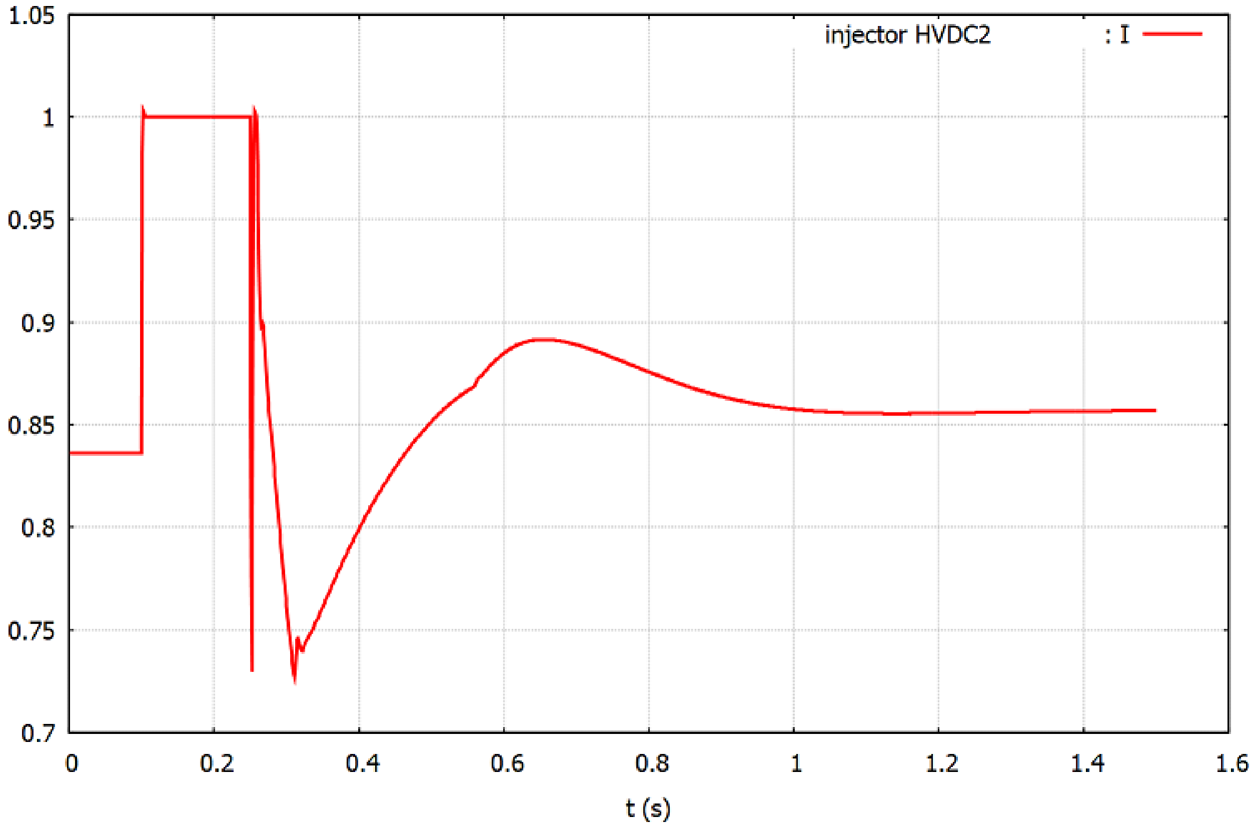
Responses of the converters in grid-following mode

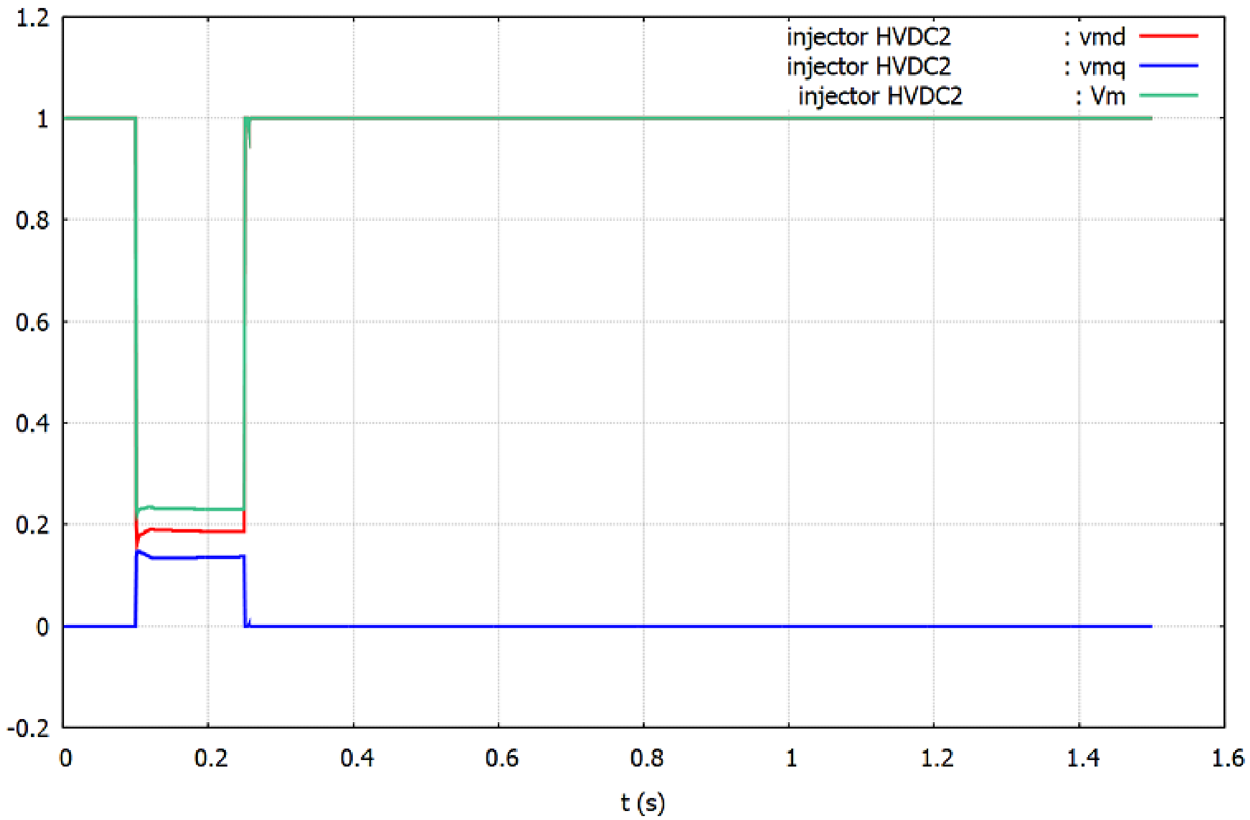




Example: large-disturbance simulation

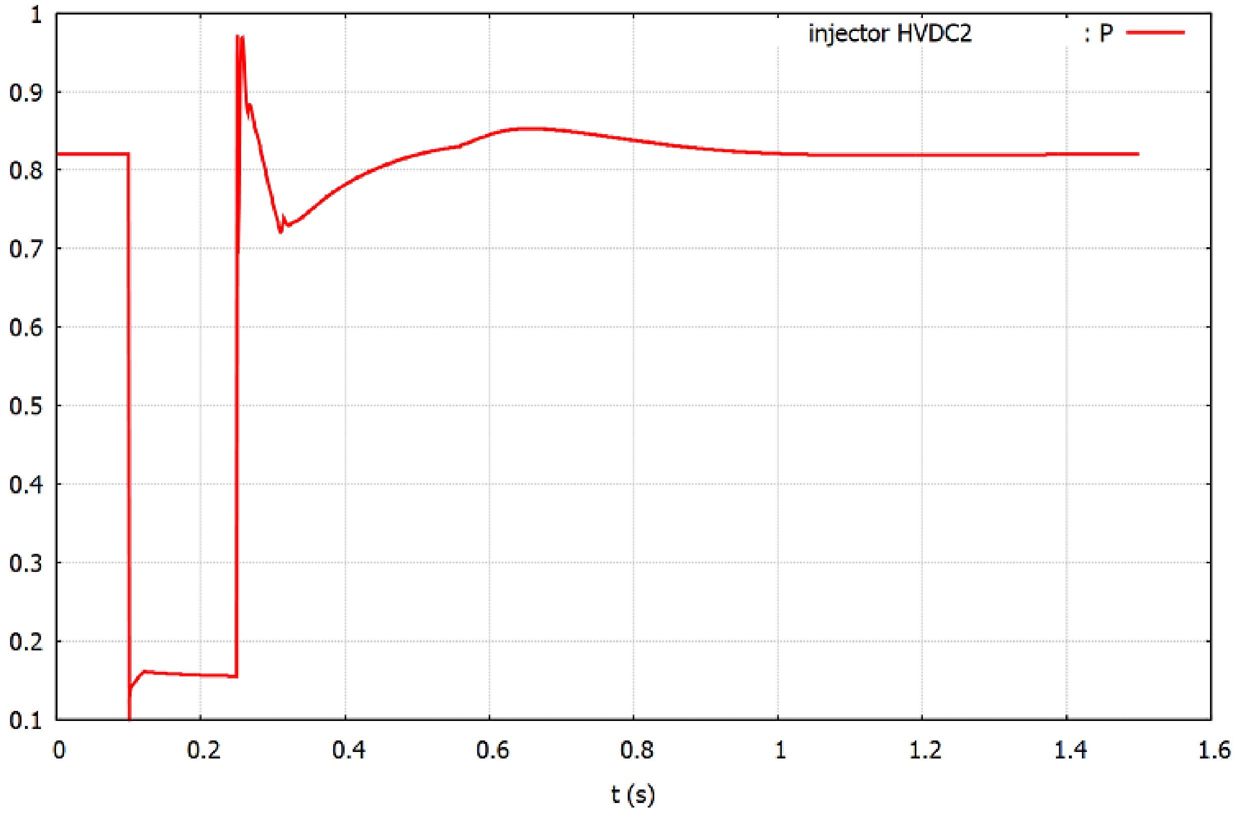
Response of the converter in grid-forming mode

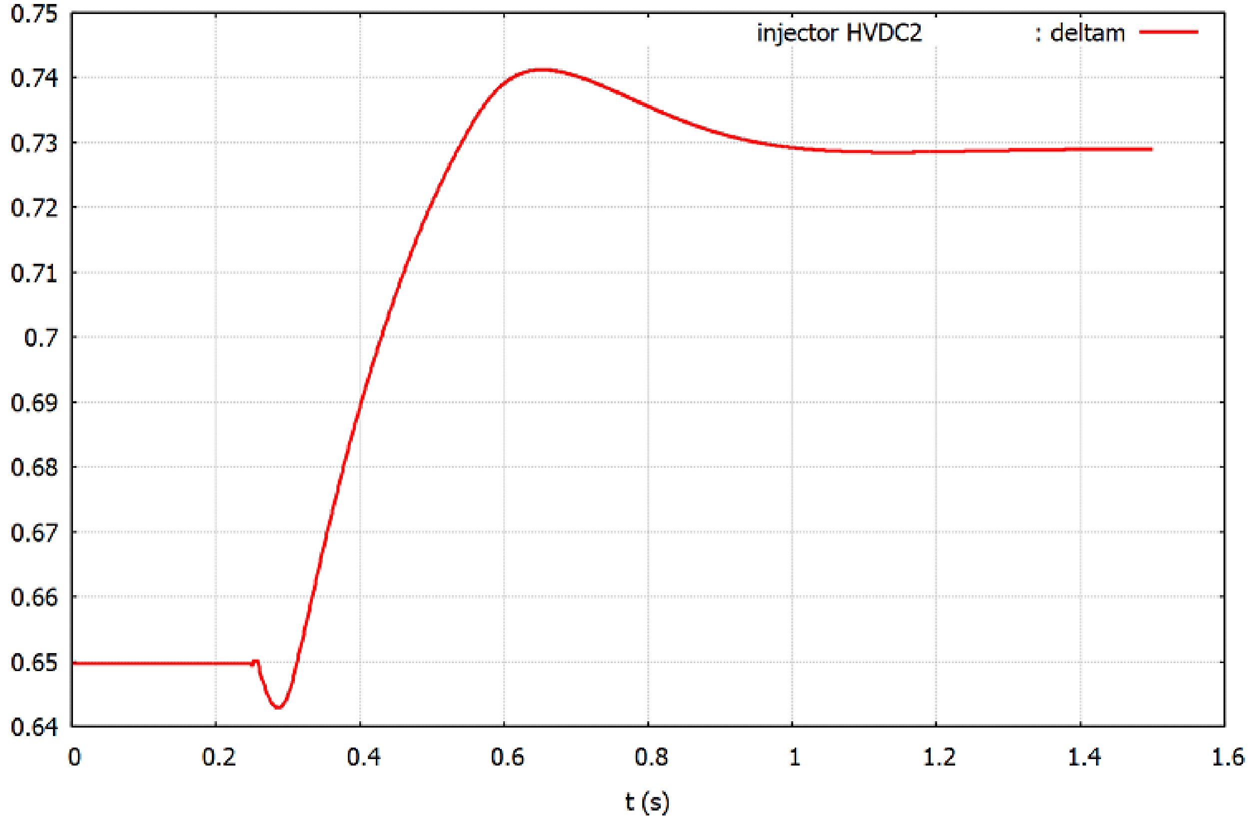




Example: large-disturbance simulation

Response of the converter in grid-forming mode





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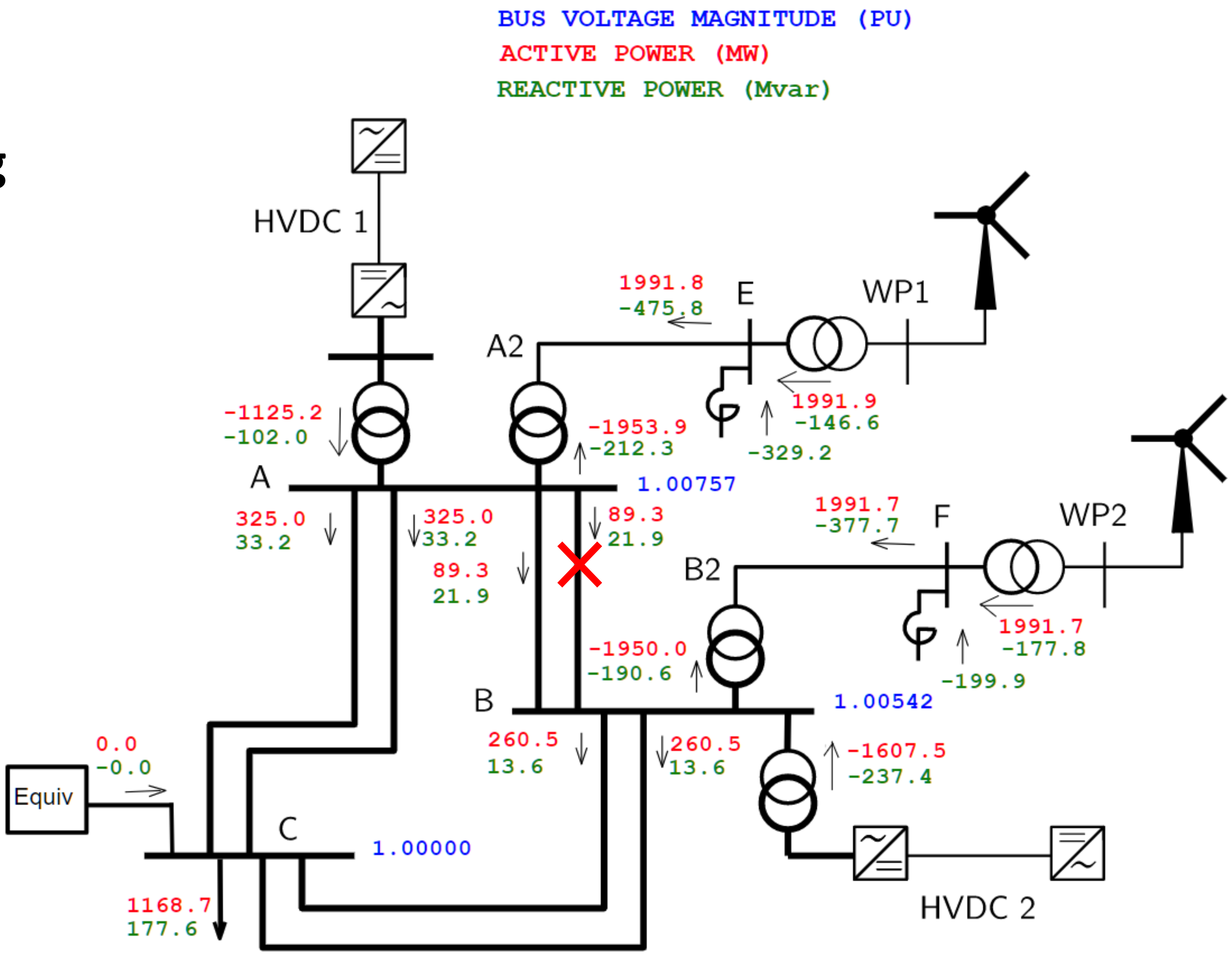
Simulation of a mild disturbance; oper. pt No. 2

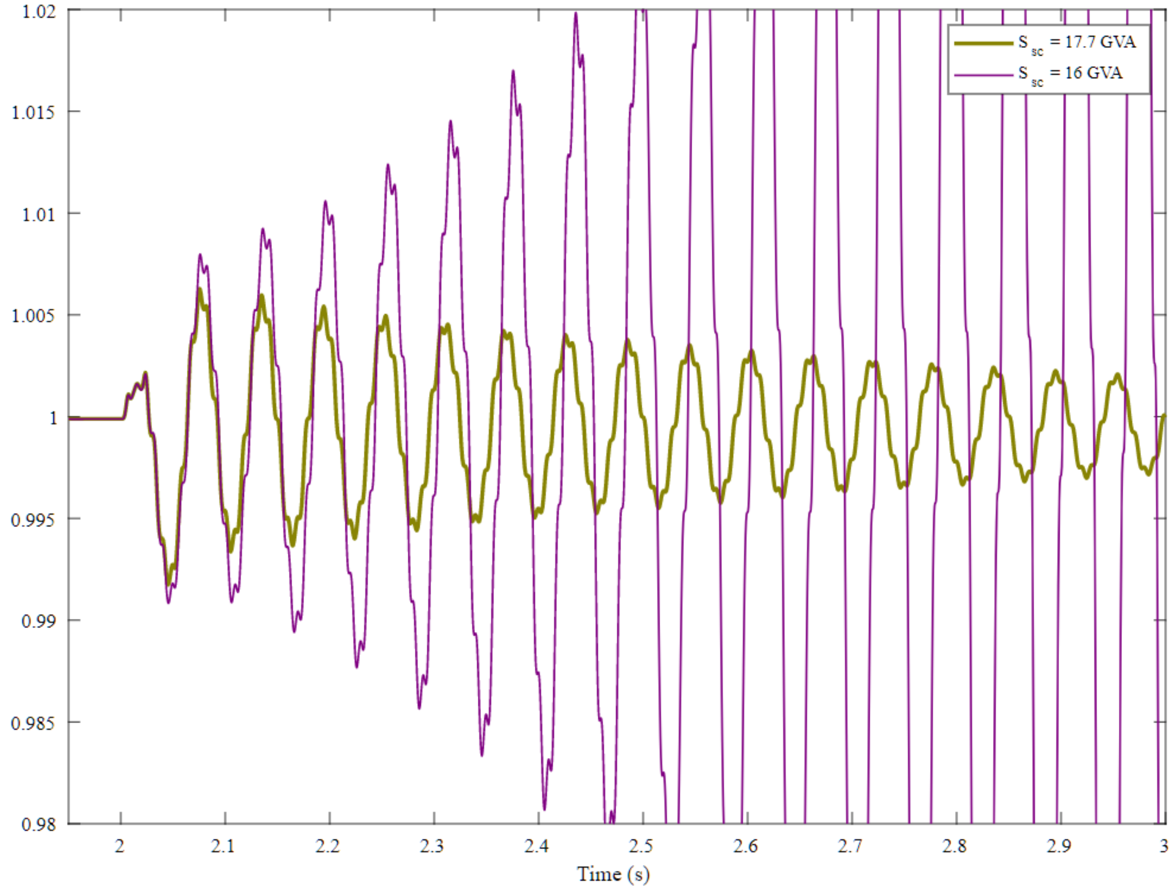
- All four converters in grid-**following** mode
- load at bus C modelled as constant admittance
- opening of one circuit between buses A and B at t= 1 s

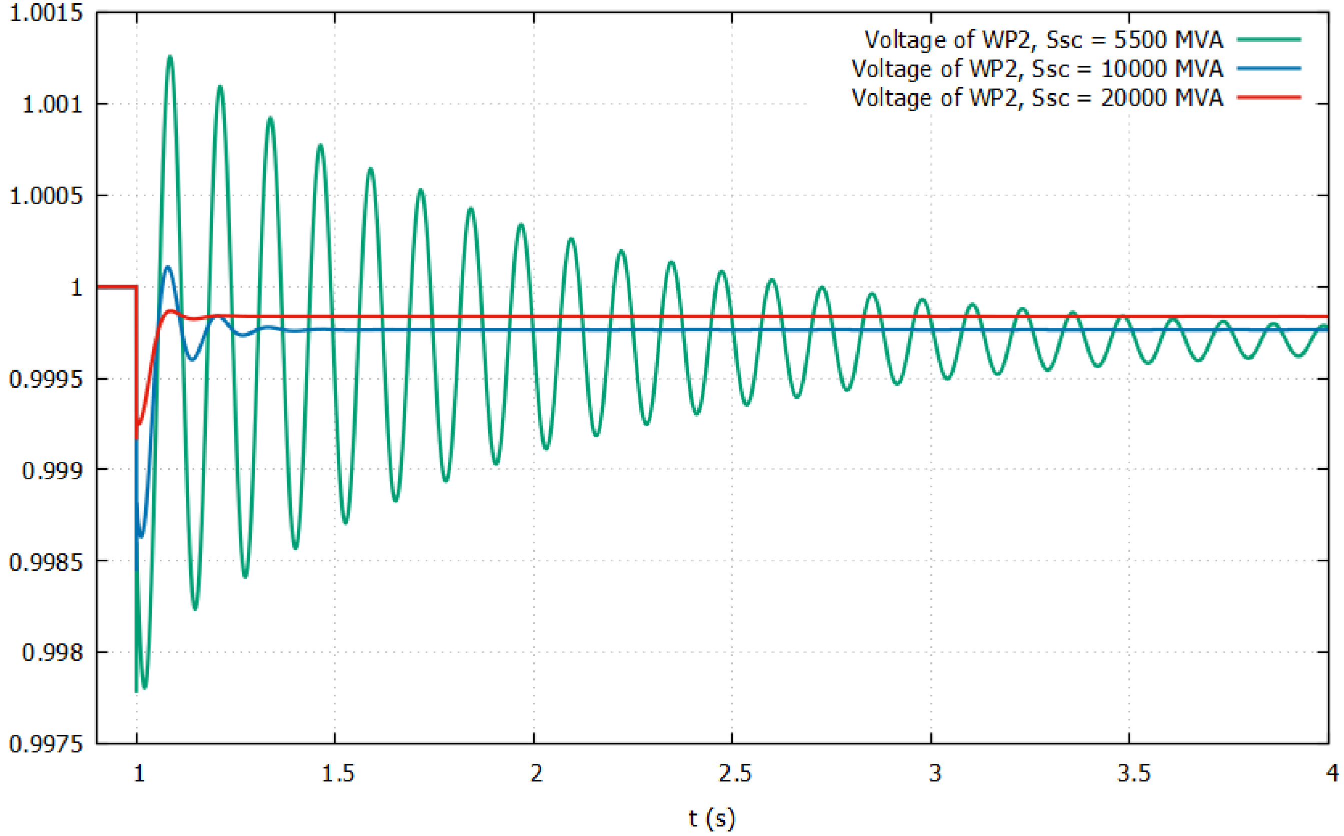
- variation of short-circuit power S_{sc} of the external equivalent



EMT vs. phasor-mode simulation

EMT model | Voltage of WP2 (pu) | *Phasor approximation*





response marginally stable for S_{sc} = 17 700 MVA

oscillation frequency ≈ 16 Hz

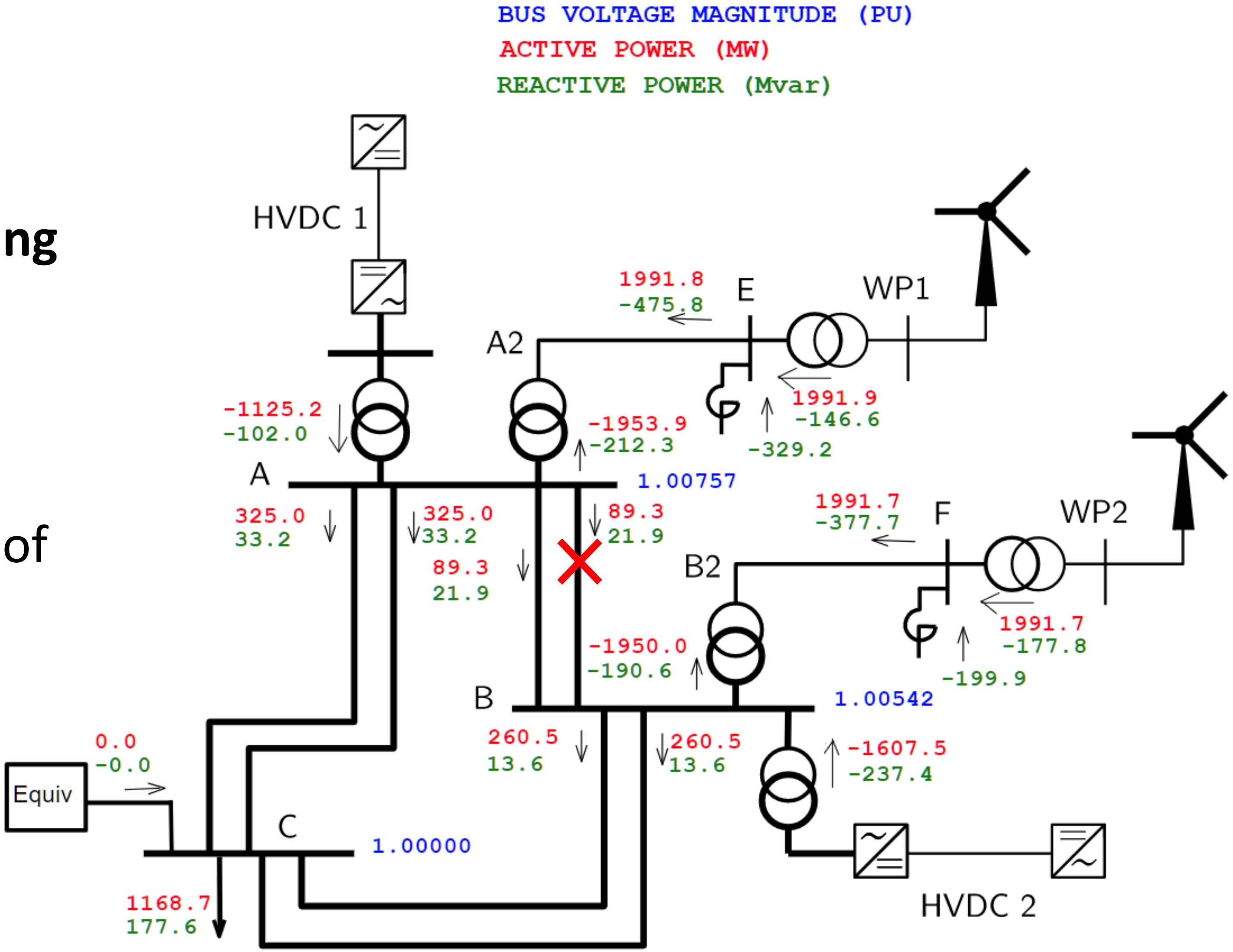
response marginally stable for S_{sc} = 5 500 MVA

oscillation frequency ≈ 8 Hz

Simulation of a mild disturbance at oper. pt No. 2

- WP2 in grid-**forming** mode
- the other three VSCs in grid-**following** mode
- same disturbance

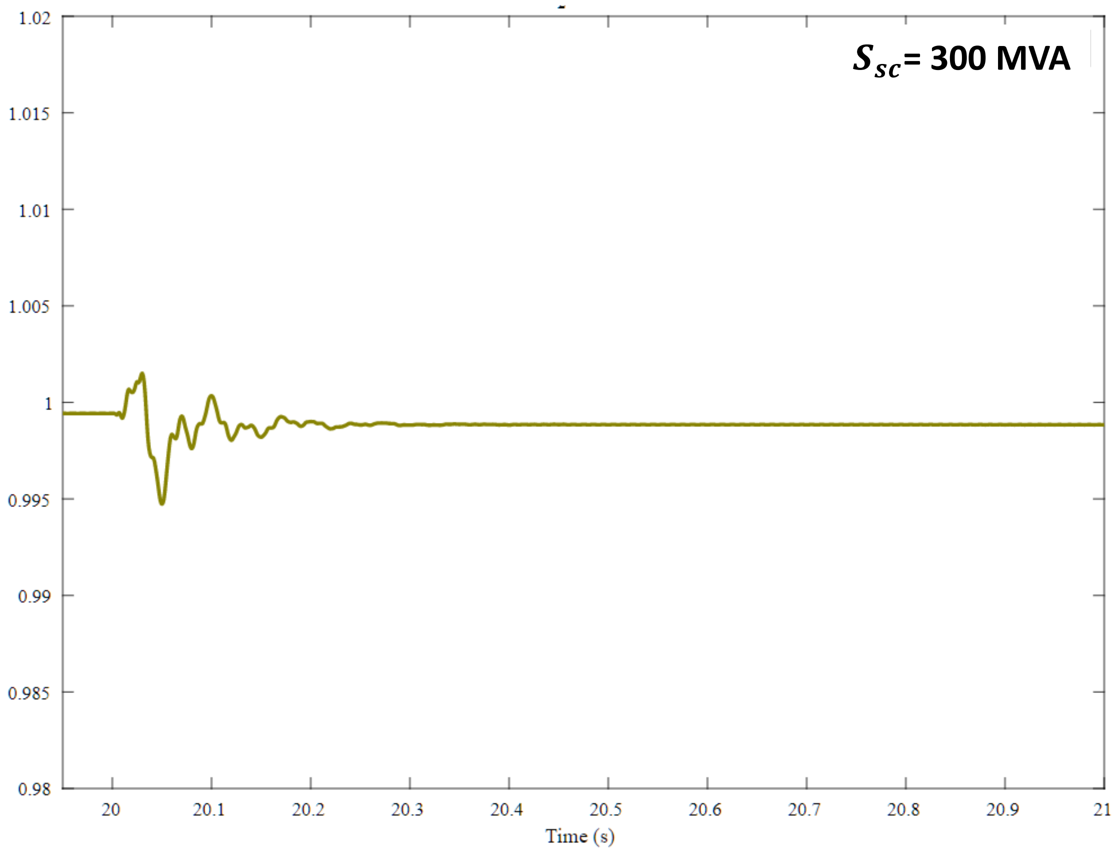
- variation of short-circuit power S_{sc} of the external equivalent



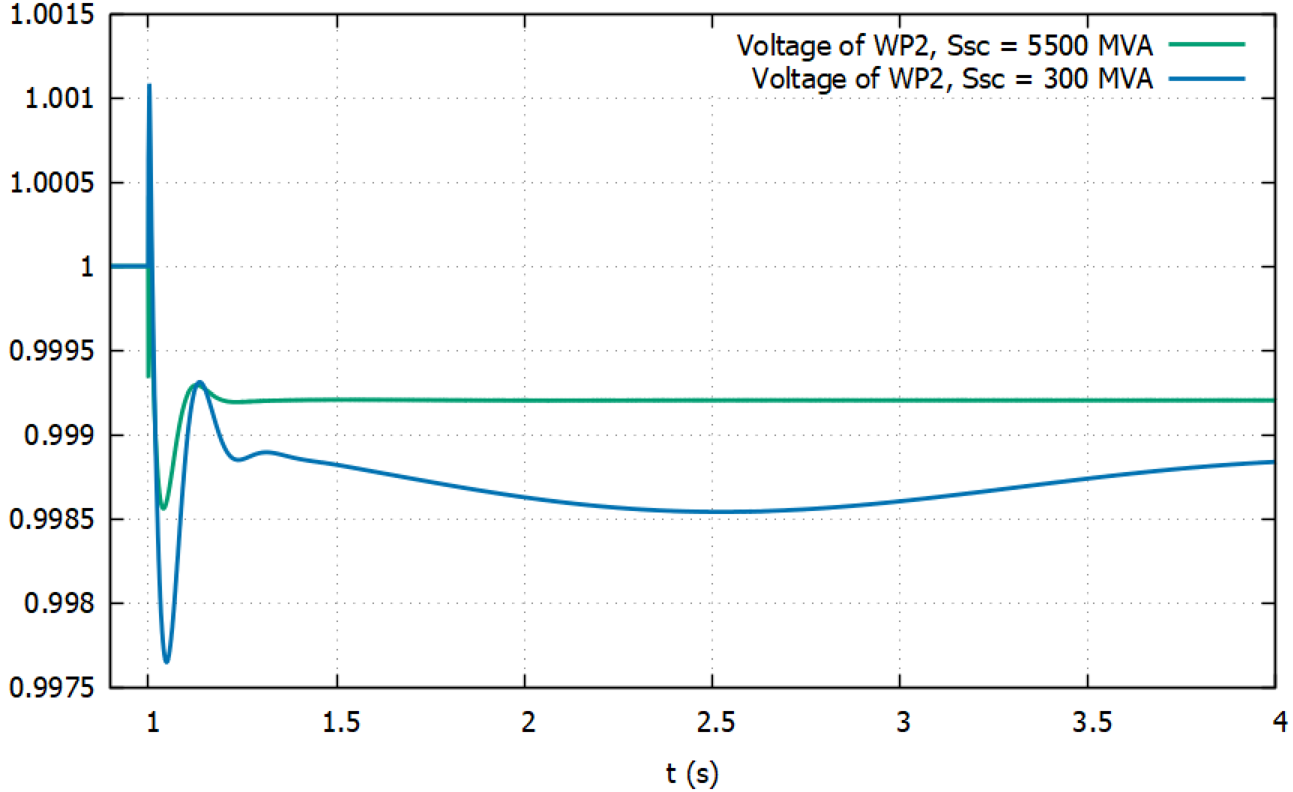
EMT vs. phasor-mode simulations

Voltage of WP2 (pu)

EMT model



Phasor approximation



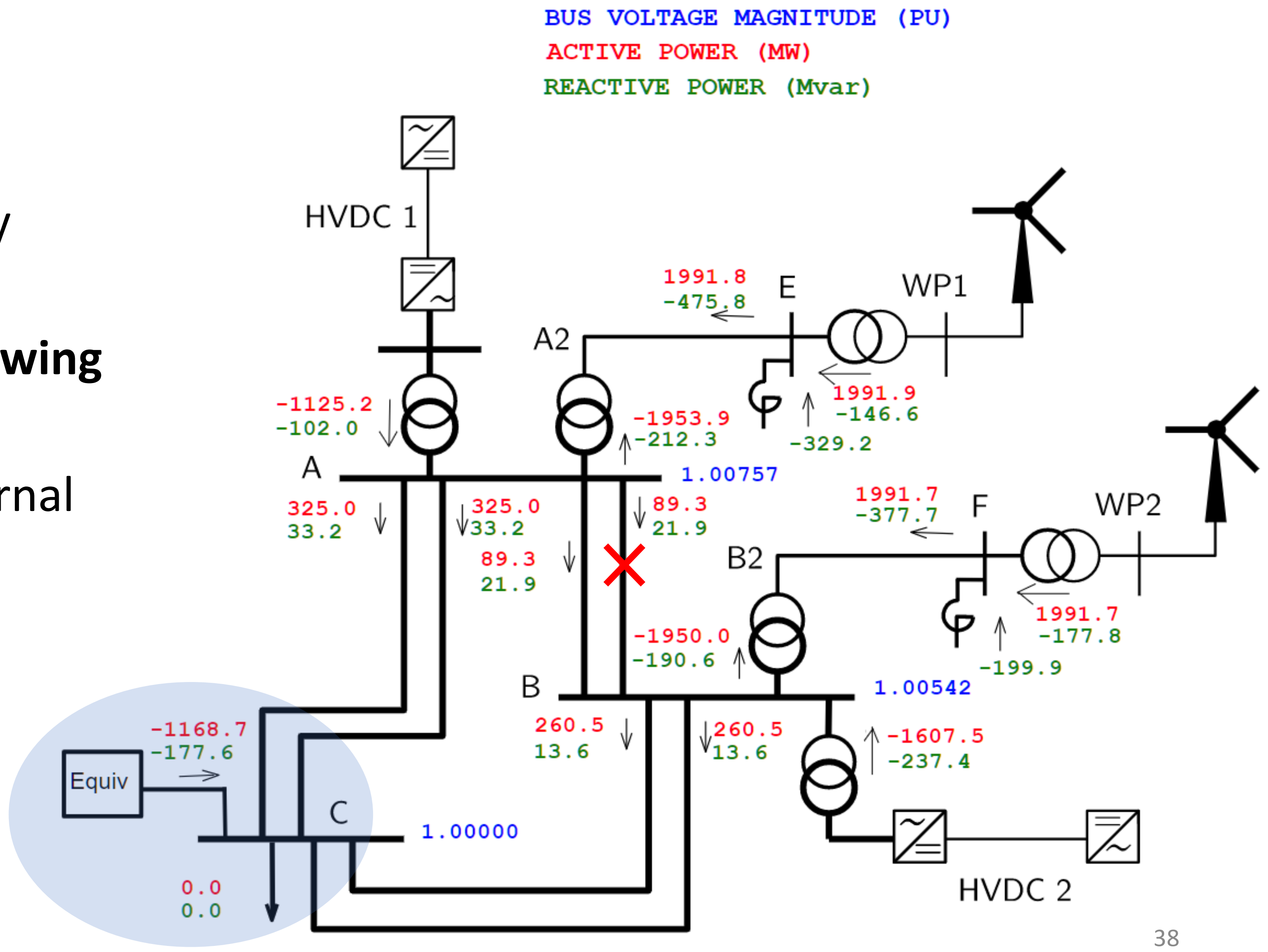
Strong stabilizing effect of grid-forming converter.

System so stable that the response is acceptable with S_{sc} as low as 300 MVA !

EMT model and phasor approximation in agreement.

Simulation of a mild disturbance at (variant of) oper. pt No. 2

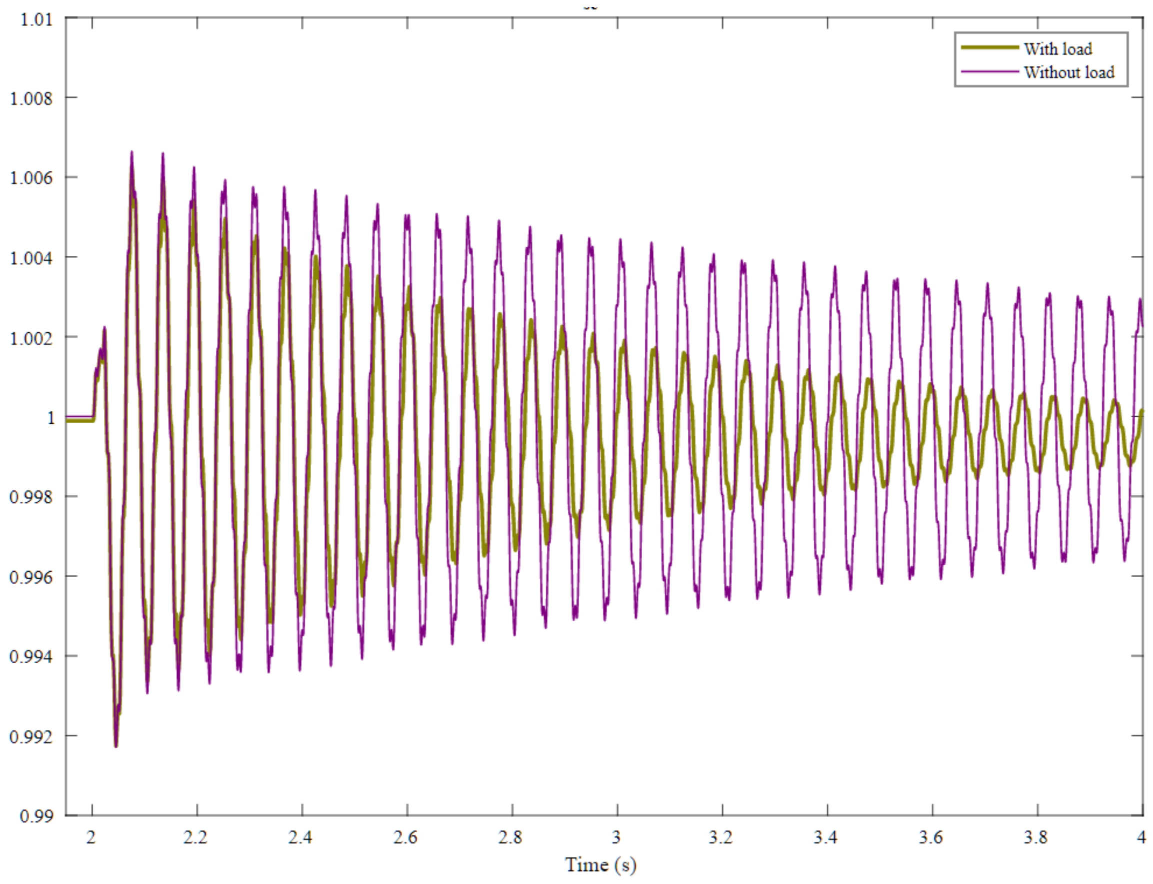
- Variant without load at bus C (corresponding power taken by external equivalent)
- All four converters in grid-**following** mode
- short-circuit power S_{sc} of external equivalent : 17 700 MVA
- same disturbance



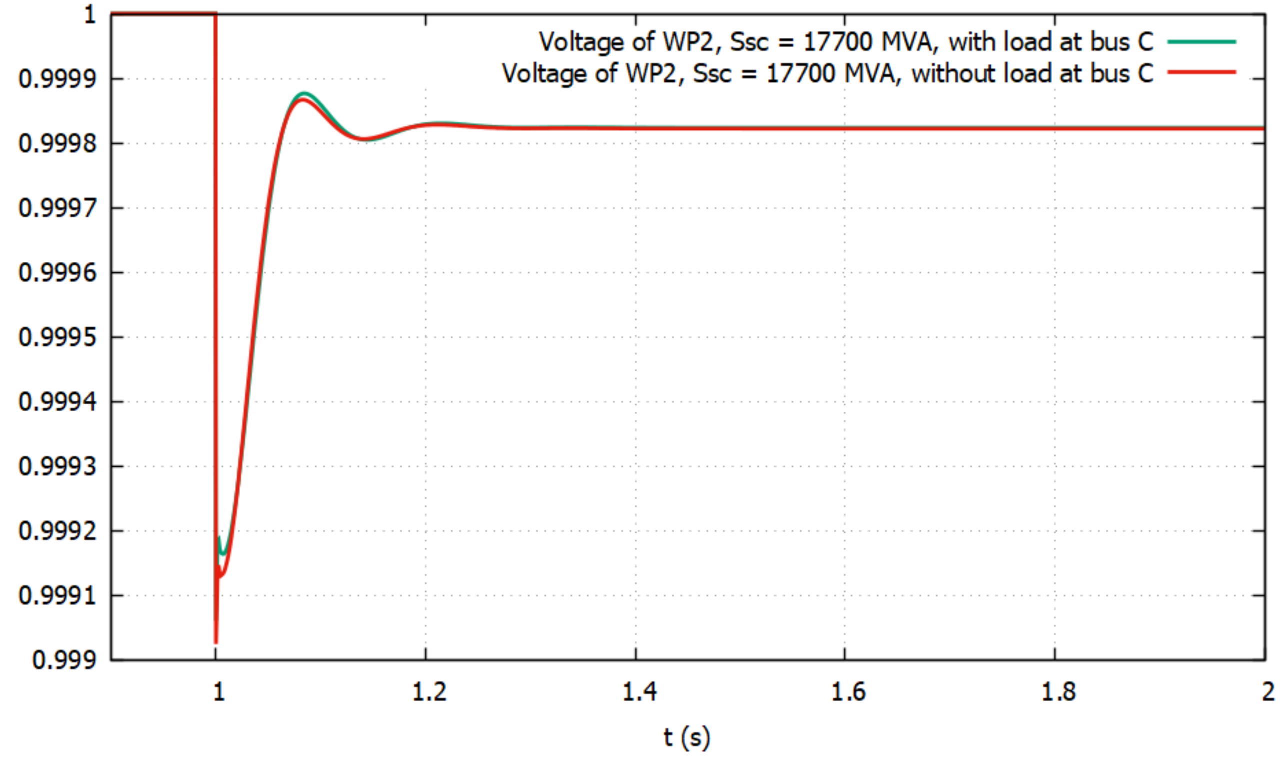
EMT vs. phasor-mode simulations

Voltage of WP2 (pu)

EMT model



Phasor approximation



Damping effect of (constant admittance) load not seen in phasor-mode simulation

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Closing words

- Significant discrepancies between EMT and phasor models in terms of stability limits
- Apparently less pronounced with grid-forming than with grid-following VSCs
  - probably due to higher system stability
  - to be further checked in large-disturbance scenarios
- Need to better understand the discrepancies between EMT and phasor models
- *Not shown in this presentation* : “spurious” transients most likely due to incoherency between differential eqs. of transformer and algebraic eqs. of network
- Indicators to complement phasor-mode simulation and raise alarms about the necessity to switch to EMT simulation ?
- Alternatives to phasor-mode simulation: dynamic phasors, co-simulation, etc.
- The proposed benchmark is well suited to validate those approaches
  - it can also be extended: e.g., with smallest STATCOM or synchronous condenser to stabilize the system

Thank you for our attention !

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