Grid forming Converters connected to the Transmission System

From general considerations to practical applications

PowerTech
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POWER FOR THE SUSTAINABLE DEVELOPMENT GOALS

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TenneT

- **Introduction of the presenters**

1. **Introduction (8:30 – 8:45) - X. Guillaud**
2. **Description of the main types of control (8:45 – 9:15) – X. Guillaud**
3. **Implementation of the grid-forming converter on a VSC and an MMC (9:15 – 9:45) – F. Colas**
4. **Current limitation in a converter driven by a grid-forming control (9:45 – 10:00) – X. Guillaud**

PAUSE

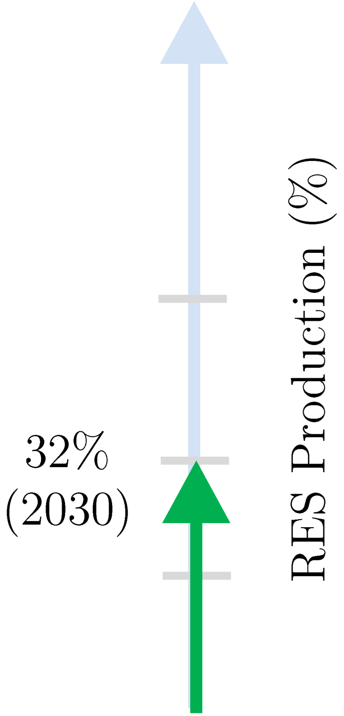
5. **Presentation of the benchmark (10:30 – 10:40) - X. Guillaud**
6. **Main applications for the grid forming control: HVDC link (10:40 – 11:00) – F. Colas**
7. **Some thinking about the headroom and required energy for a grid-forming application (11:00 – 11:10) – X. Guillaud**
8. **The integration of grid forming capabilities into connection network codes (11:10 – 11:50) – M.Ndreko**
9. **Conclusion and perspectives (11:50 – 12:00) - F. Colas**

Xavier Guillaud - professor in Centrale Lille . He received his Ph.D from University of Lille in 1992 and joined the Laboratory of Electrical Engineering and Power Electronic (L2EP) in 1993. He has been professor in Ecole Centrale of Lille since 2002. First, he worked on modeling and control of power electronic systems. Then, he studied the integration of distributed generation and especially renewable energy in the power system. Nowadays, he is focused on the integration of high voltage power electronic converters in the transmission system. He is involved on several projects about power electronic on the grid within European projects and a large number of projects with French electrical utilities.

Frederic Colas : Research engineer – Arts et Metiers. He received a PhD in control system in 2007 from Ecole Centrale de Lille (France). Frédéric Colas is a member of the Laboratory of Electrical Engineering (L2EP) in Lille and is a Research Engineer at Arts et Métiers. His field of interest includes the integration of dispersed generation systems in electrical grids, advanced control techniques for power system, integration of power electronic converters in power systems and hardware-in-the-loop simulation.

Mario Ndreko – Tennet. He received his Ph.D degree in Electrical Engineering from Delft University of Technology, Delft, Netherlands in 2017 on the topic of grid connection code compliance and control optimisation for offshore wind power plants with HVDC transmission. Since 2017 he is with TenneT TSO GmbH in Germany. He is involved in activities within TenneT and ENTSO-E for the development of methodologies enabling the secure operation of the power system with up to 100% inverter-based generation. In addition, he is Lead of the ENTSO-E technical guidance team of the steering group connection network codes (StG CNC).

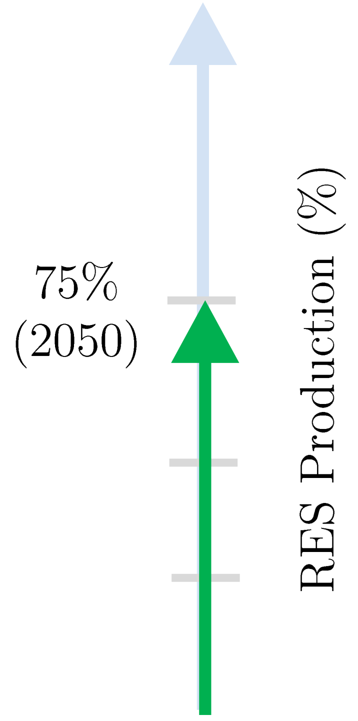
Introduction : Large increase of Renewable Power sources in the electrical production breakdown



Objective -40% CO_2 in 2030 compared to 1990

[1] https://ec.europa.eu/clima/policies/strategies/2030_en

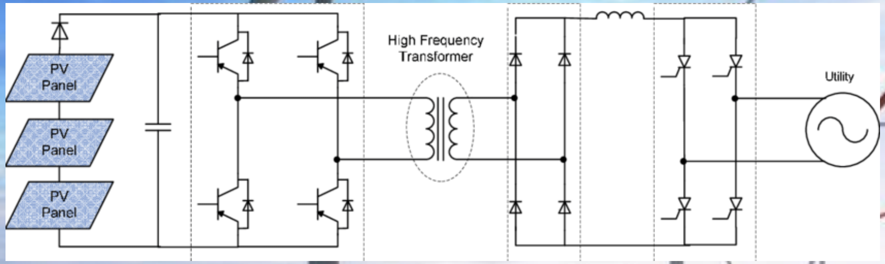
Introduction : Large increase of Renewable Power sources in the electrical production breakdown

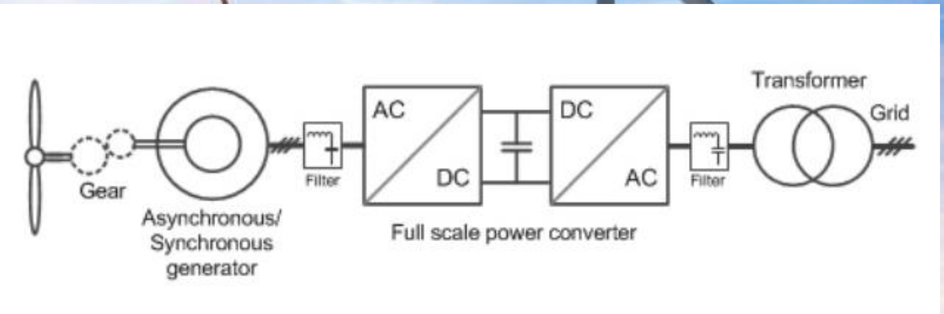


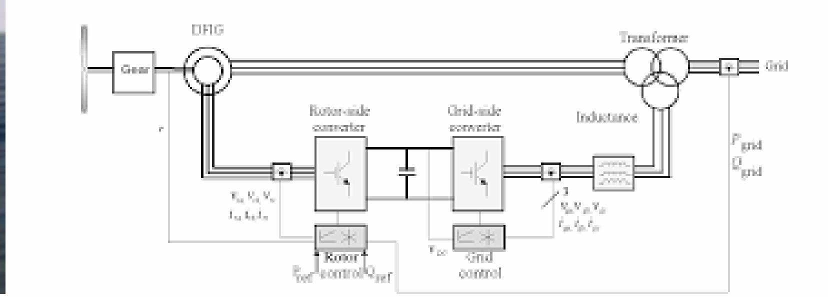
Objective -40% CO_2 in 2030
compared to 1990

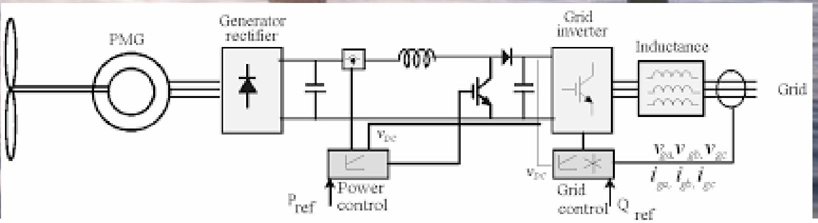
[1] https://ec.europa.eu/clima/policies/strategies/2030_en

Nowadays, nearly all the main renewable energy sources are connected to the grid thanks to power electronics.









Since the renewable energy sources are not always located next to the consumption, there is a huge need to develop some new transmission capacity.

Most of them will be developed thanks to the HVDC technology

In the North Sea :

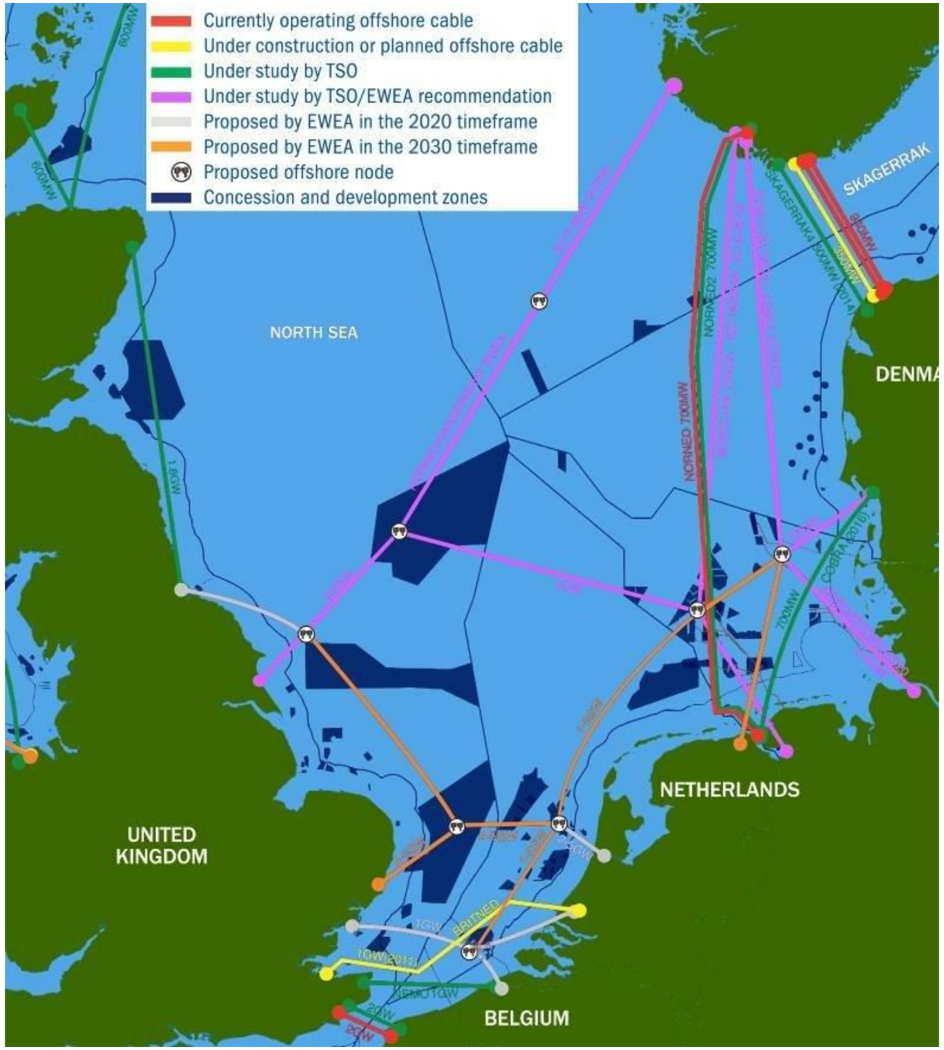
Undersea HVDC links :

Nemo, Kriger Flaks …

Off shore wind farms

Borkum, Gode Wind …

In the future Dogger Bank …

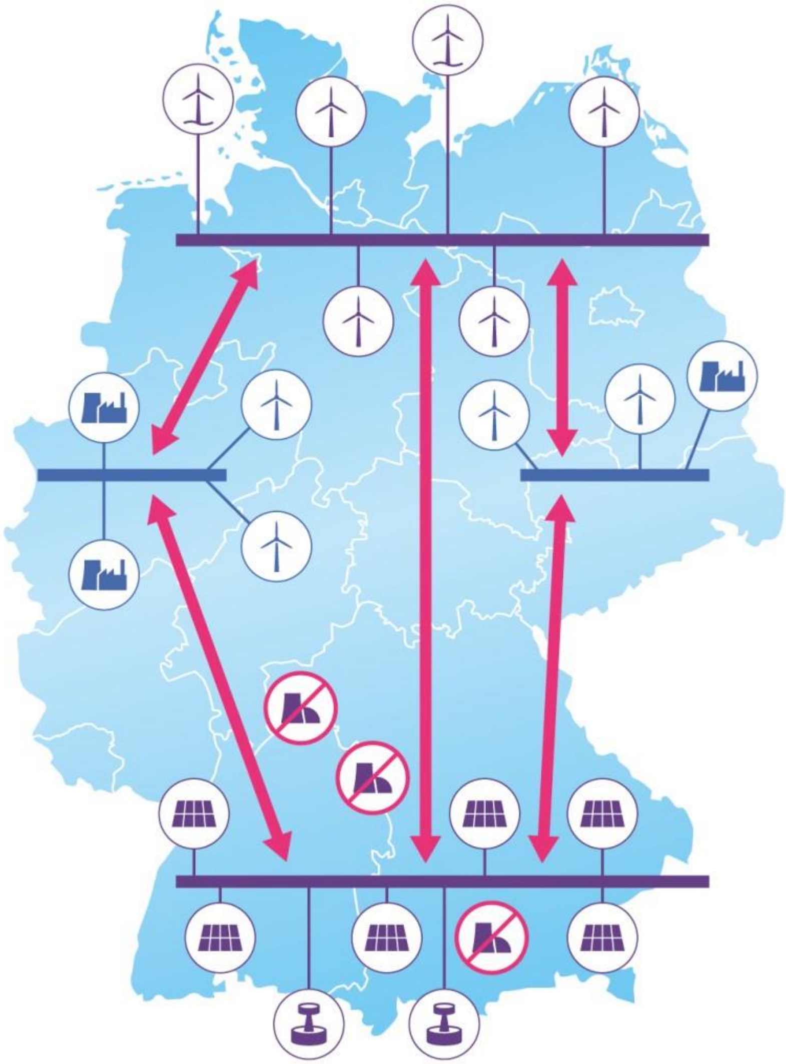


Wind Europe "Oceans of opportunity: Harnessing Europe's largest domestic

Since the renewable energy sources are not always located next to the consumption, there is a huge need to develop some new transmission capacity.

Most of them will be developed thanks to the HVDC technology

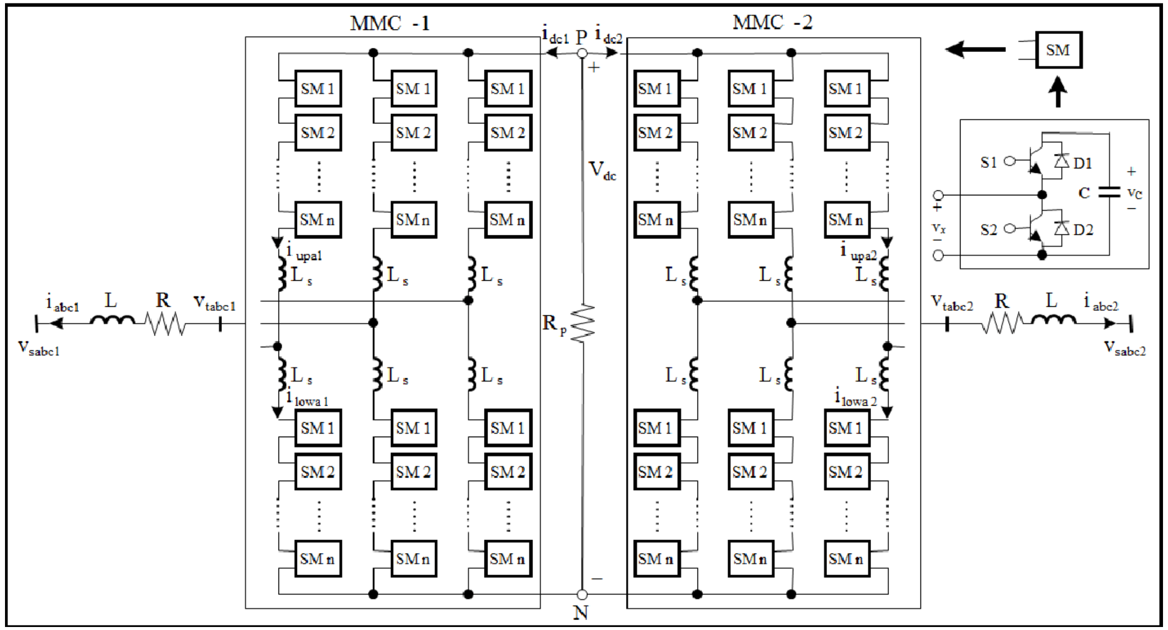
On shore links : example of Germany

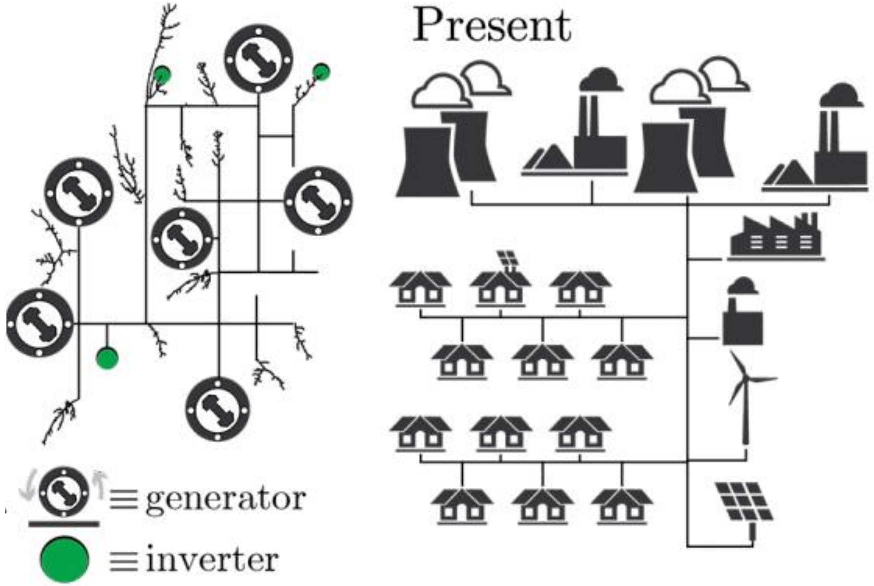


https://www.amprion.net/Grid-expansion/

Nowadays, most of the new transmission capacity are developed with the HVDC technology

The Modular Multilevel Converter is now a state of art technology for this purpose



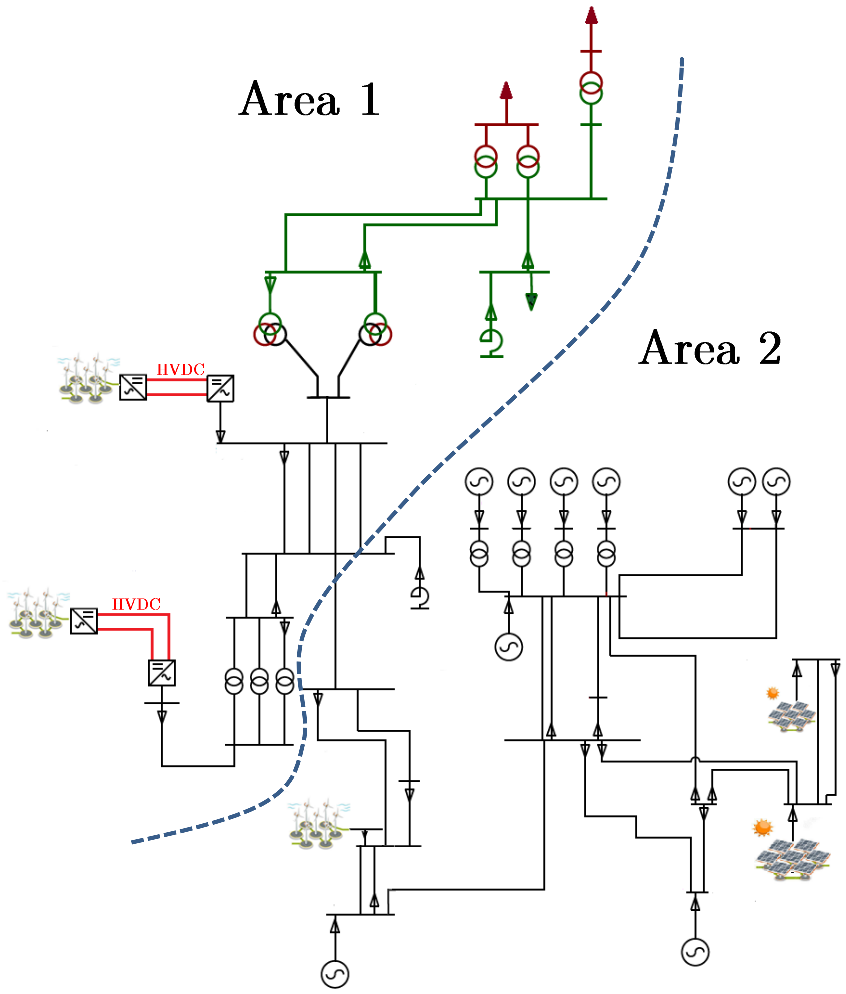


Power System dominated by
Synchronous machines

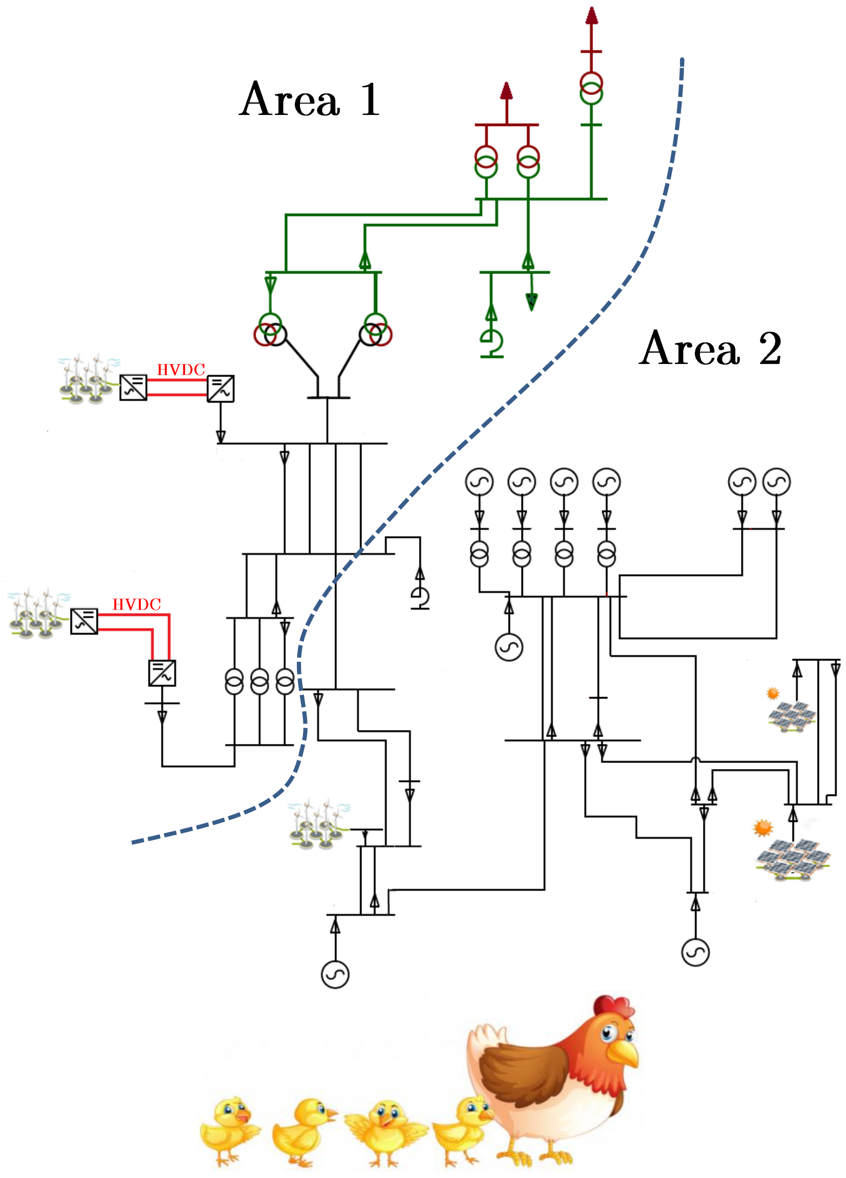
- Inherent synchronization of the power sources
- Control of frequency and voltage
- Rotating Inertia
- High overcurrent capability: large short circuit current

To be synchronized, the Power converters connected to the present AC system relies on AC voltage formed by synchronous machine

Grid-following concepts

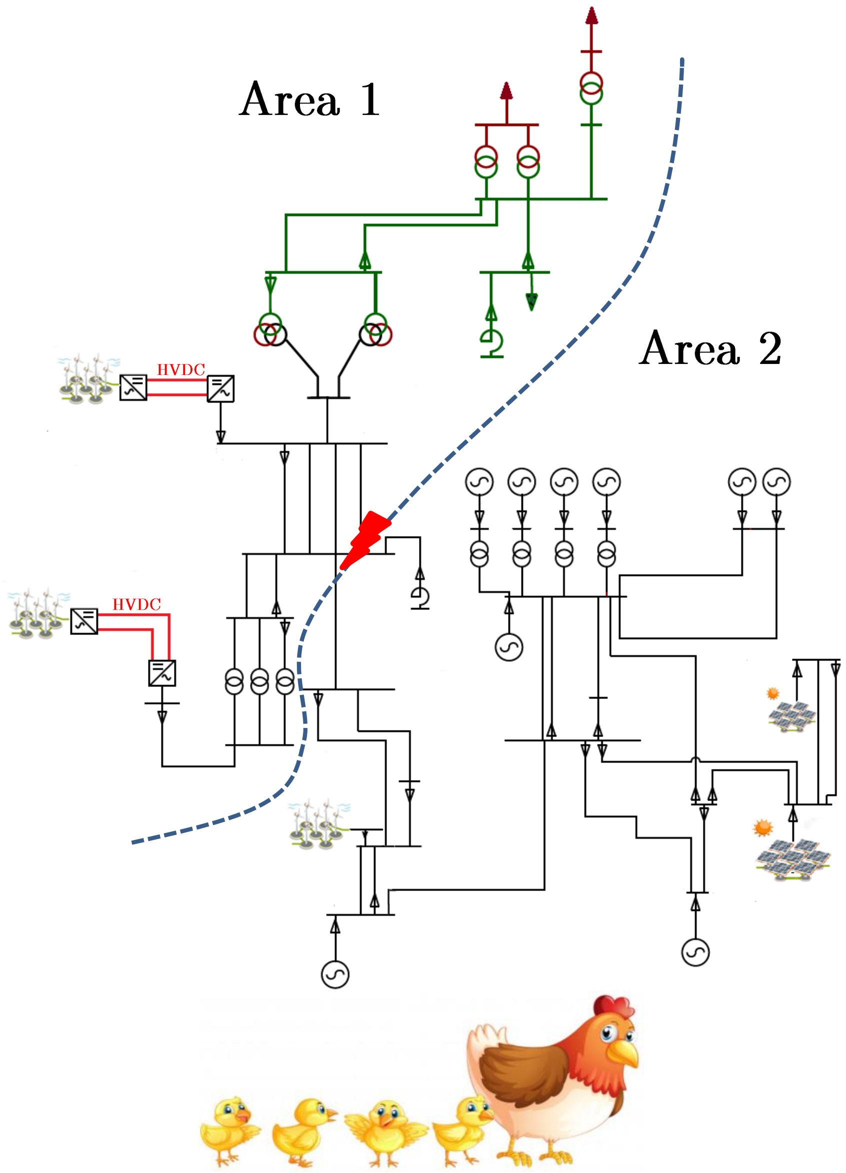


- Let’s imagine a grid with a large integration of power electronic converter.
- Let’ suppose that no synchronous machines are connected on Area 1



- Let's imagine a grid with a large integration of power electronic converter.
- Let' suppose that no synchronous machines are connected on Area 1

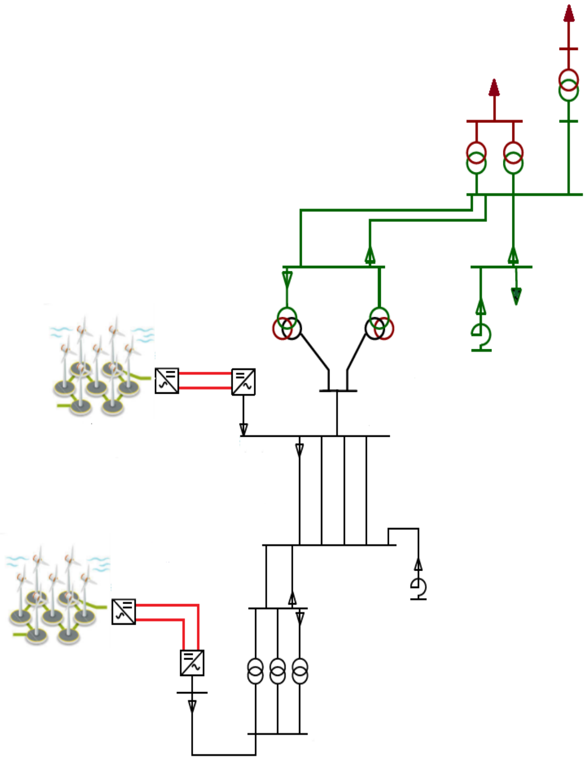
- The converters are synchronized to the synchronous machines connected to Area 2



- Let's imagine a grid with a large integration of power electronic converter.
- Let' suppose that no synchronous machines are connected on Area 1

- The converters are synchronized to the synchronous machines connected to Area 2

- A Fault occurs on a line, resulting in a line tripping
- Separation of the network in two areas



- The Area 1 is supplied with 100 % Power electronic converter

Loss of synchronism

⇩

Risk of instability

Description of the main types of control

The following presentation is a summary of the work done on the grid-forming control which started about 6 years ago in our lab.

After various studies on different control laws, we found that most of the different solutions which are proposed in the literature were nearly the same and it was very important to :

1. **Come back to the basics in order to define the fundamental principle of the grid-forming control**
2. **Build a simple and coherent theory which highlights all the possible degrees of freedom**
3. **Think about current limitation and resynchronization with the grid forming control**

As it is well known, there are two mains types of power electronic converters are connected to the AC grid :

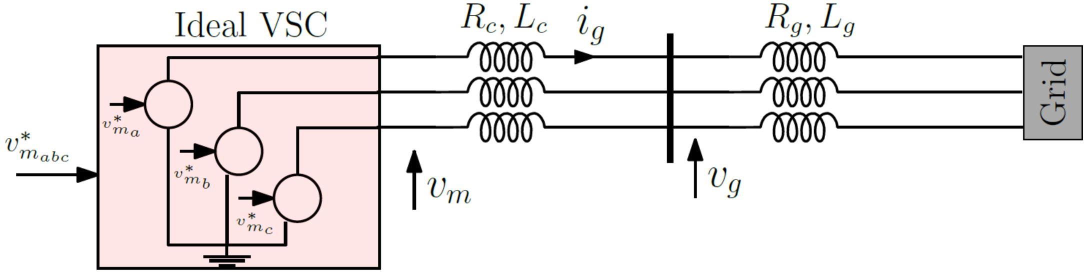
2-Level Voltage source converters

NPC Voltage source converters

VSC-MMC

In a first step, an ideal VSC is considerered:

This ideal VSC is assimilated to a driven three-phase voltage source



In the following applications, the converter is supposed to be connected to a transmission system with a 0.15 pu connection impedance

Forewords :

Till now, there is not a single definition of the grid forming control fully accepted by every body. The following slides are proposing a definition based on the use of a voltage source.

Grid forming = voltage source

but a grid forming converter has always to **control the power** which is exchanged between the DC and AC grid.

What is the role of a power converter ?

#1 Exchanging **active power** with the grid

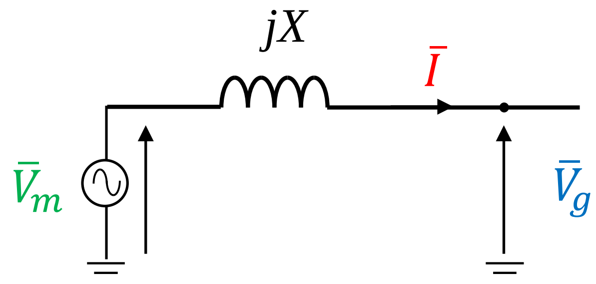
#2 For a number of them : Providing some **ancillary services** (voltage support, frequency support …)

The control of the **active power** is a key point in the control of a VSC.

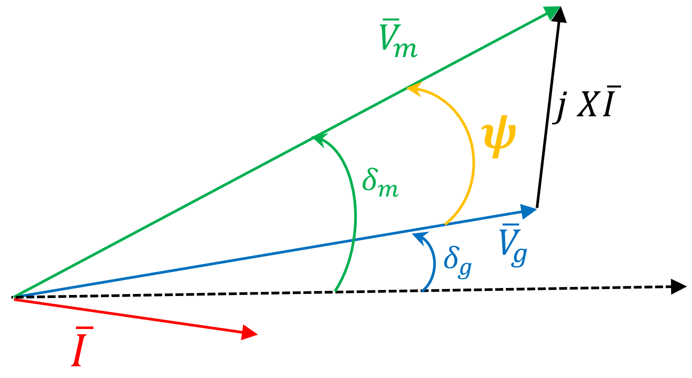
This key requirement has to be included in the grid forming control.

Let's recall the well-known **voltage** formulation

$$P = \frac{V_g V_m}{X} sin(\delta_m - \delta_g)$$



$\bar{V}_m = V_m\, e^{j\delta_m}$ $\bar{V}_g = V_g\, e^{j\delta_g}$



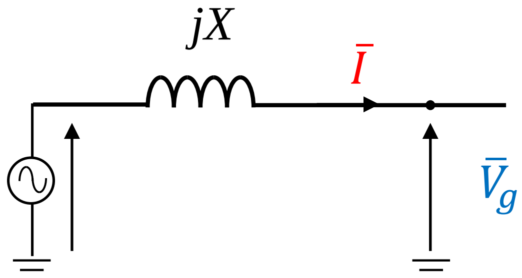
Neither V_g not δ_g can be modified directly by the control.

A modification on V_m has a strong influence on the reactive power

δ_m **is the only way to control the active power**

This is the origin of the grid-forming control

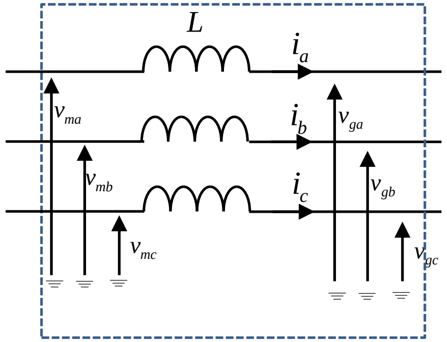
Phasor quasi static model



$\bar{V}_m = V_m\, e^{j\delta_m}$ $\qquad$ $\bar{V}_g = V_g\, e^{j\delta_g}$

Dynamic EMT model

$$v_{ma}(t) = V_m\sqrt{2}\sin(\omega_m t + \delta_m)$$
$$v_{mb}(t) = V_m\sqrt{2}\sin(\omega_m t - 2\pi/3 + \delta_m)$$
$$v_{mc}(t) = V_m\sqrt{2}\sin(\omega_m t - 4\pi/3 + \delta_m)$$



$$v_{ga}(t) = V_g\sqrt{2}\sin(\omega_g t + \delta_g)$$
$$v_{gb}(t) = V_g\sqrt{2}\sin(\omega_g t - 2\pi/3 + \delta_g)$$
$$v_{gc}(t) = V_g\sqrt{2}\sin(\omega_g t - 4\pi/3 + \delta_g)$$

In steady state : $\omega_m = \omega_g = \omega_b$

v_{ma}, v_{mb}, v_{mc} are a modulation of the DC bus voltage

The lower level control is designed such as

$$\langle v_{ma}\rangle_{T_e} \approx v_{ma}^*$$
$$\langle v_{mb}\rangle_{T_e} \approx v_{mb}^*$$
$$\langle v_{mc}\rangle_{T_e} \approx v_{mc}^*$$

$$v_{ma}^*(t) = V_m\sqrt{2}\sin(\omega_m t + \delta_m)$$
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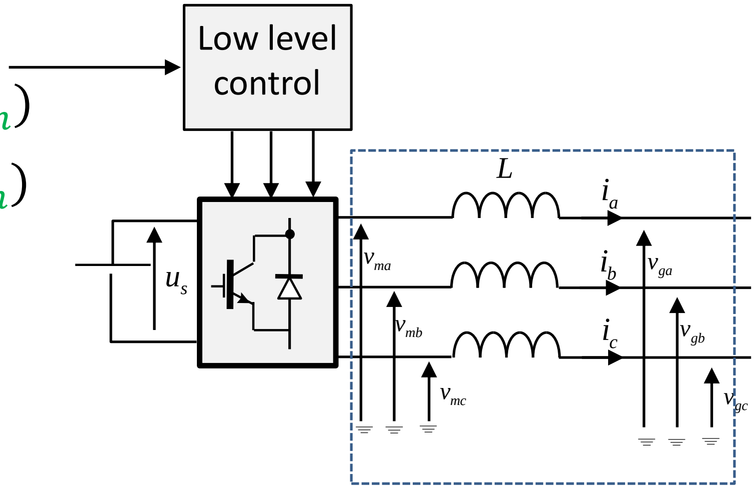

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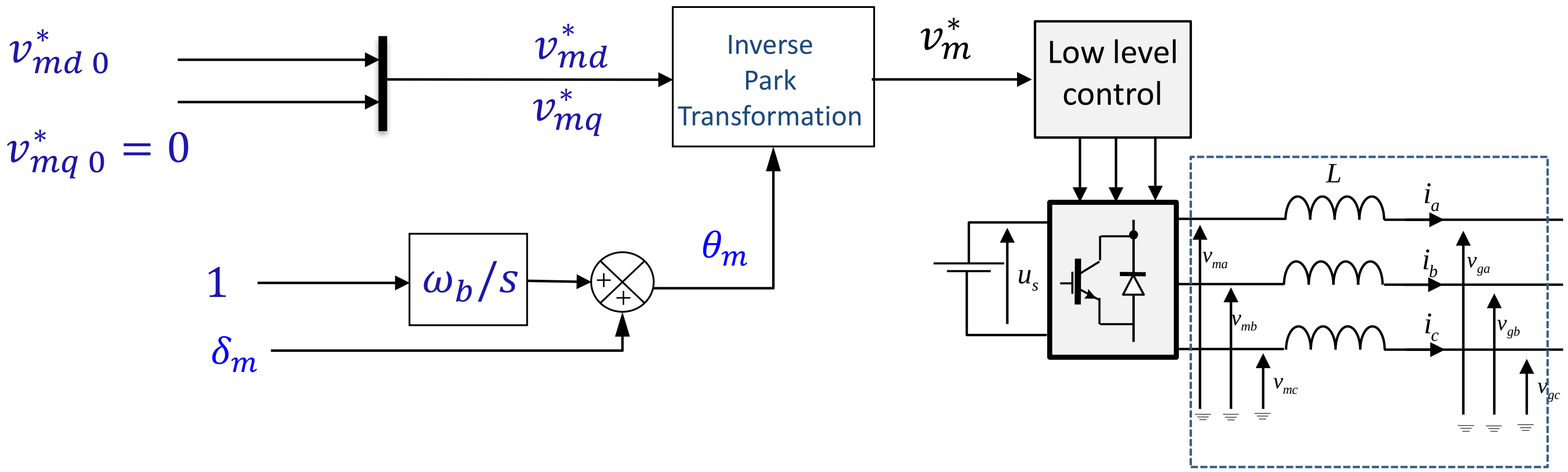
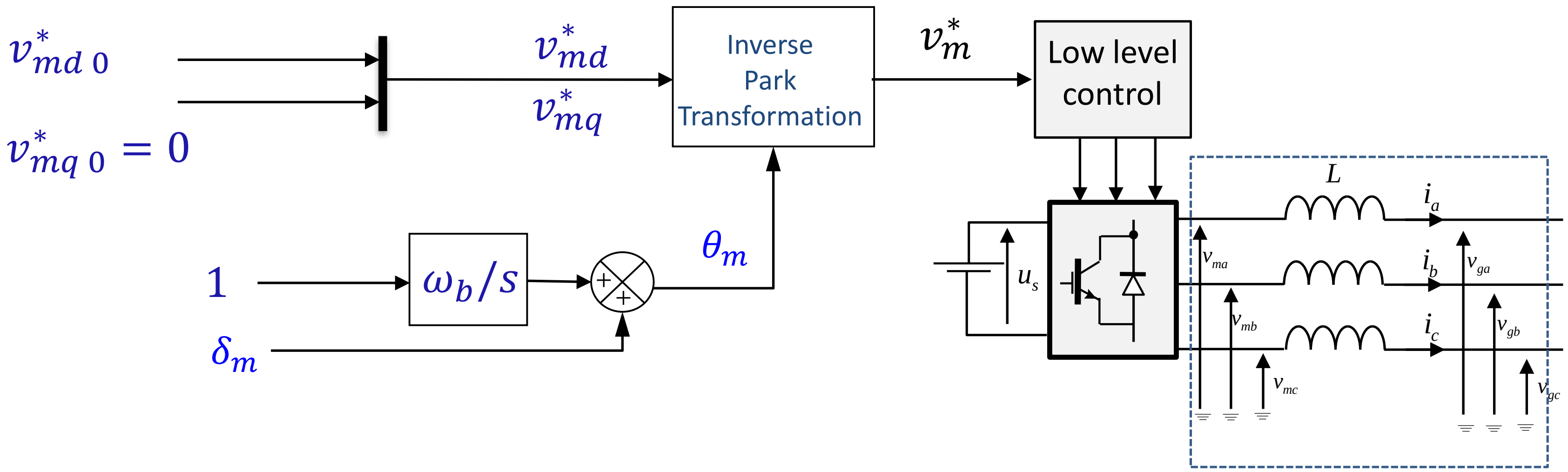


In dq frame, it is possible to control δ_m thanks to the in the following control



In the following slides, all the models are considered in per unit.

The base voltage is the nominal voltage of the grid.

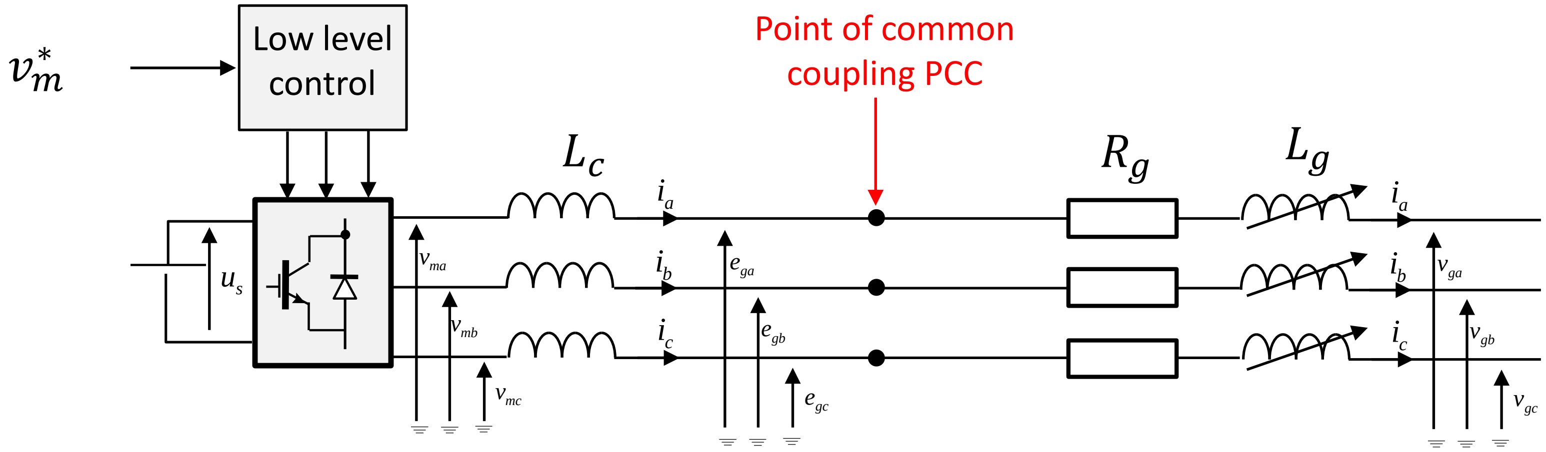
The grid voltage is considered to be equal to its nominal value : $V_{g\,pu} = 1$

The base power is the nominal power of the converter Sn

The base frequency ω_b is equal to the nominal frequency

Discussion about the connection impedance

$$L = L_c + L_g$$



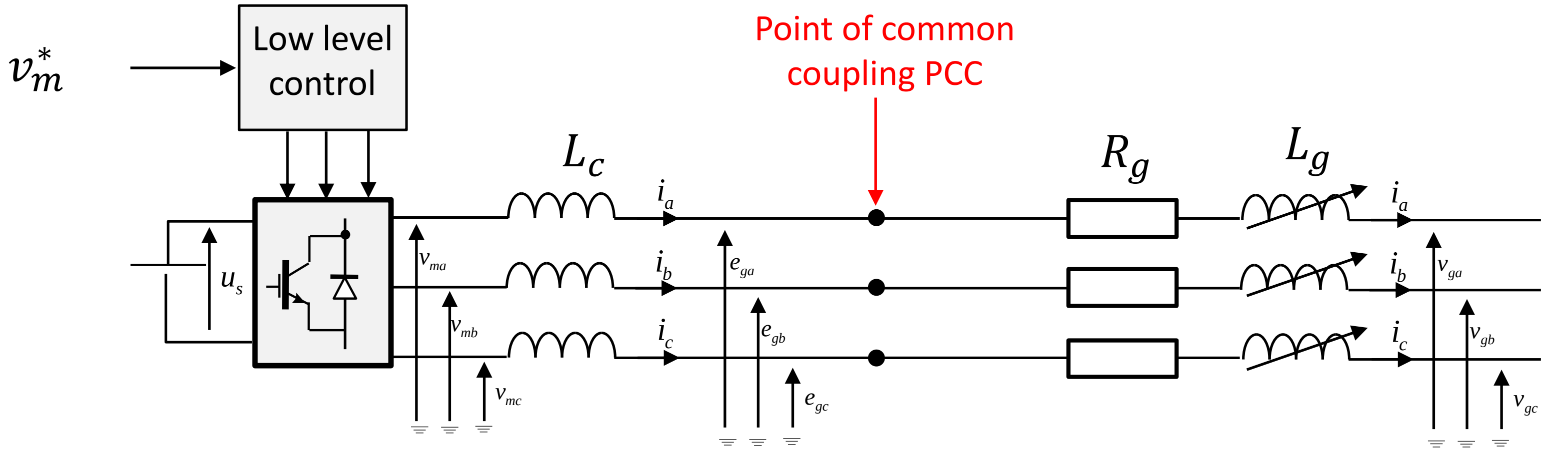
Internal impedance

leakage inductance transformer

Grid impedance

Discussion about the connection impedance

$$L = L_c + L_g$$



Internal impedance 0,15 pu

leakage inductance transformer

Grid impedance

In transmission grid $R_g \ll L_g \omega_g$

R_g is neglected in the following slides

$$X_g = R_g + j\, L_g \omega_g$$

$$X_g \approx j\, L_g \omega_g$$

In per unit

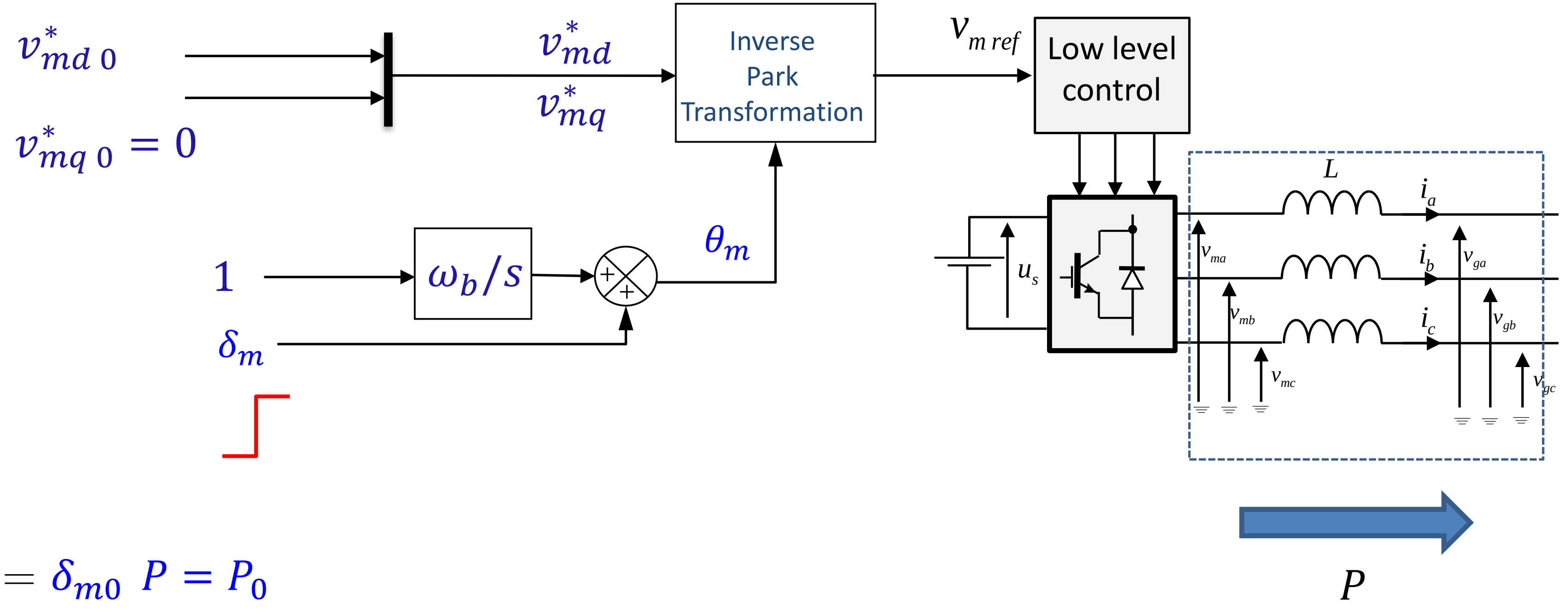
$$X_{g\ pu} \approx j\, L_{g\ pu}$$

The grid impedance depends on the short circuit power Scc of the grid at PCC $S_{cc} = 3\dfrac{V_g^2}{X_g}$

The Short Circuit Ratio is defined as : SCR = Sn/Scc

In per unit $\Rightarrow$ $\dfrac{S_{cc}}{S_n} = SCR = \dfrac{1}{X_{g\_pu}}$

In the following slides, all the equations are in per unit. For the sake of simplicity, the « pu » index is removed



t= 0 $\delta_m = \delta_{m0}$ $P = P_0$

Let's apply a step $\Delta\delta_m$ on δ_m

This implies a variation on the active power

$$\Delta P = \frac{V_g V_m}{X}\sin(\Delta\delta_m) \approx \frac{V_g V_m}{X}\Delta\delta_m$$

Numerical application

$V_g = 1$ $V_m \approx 1$

L = X = 0,2 pu

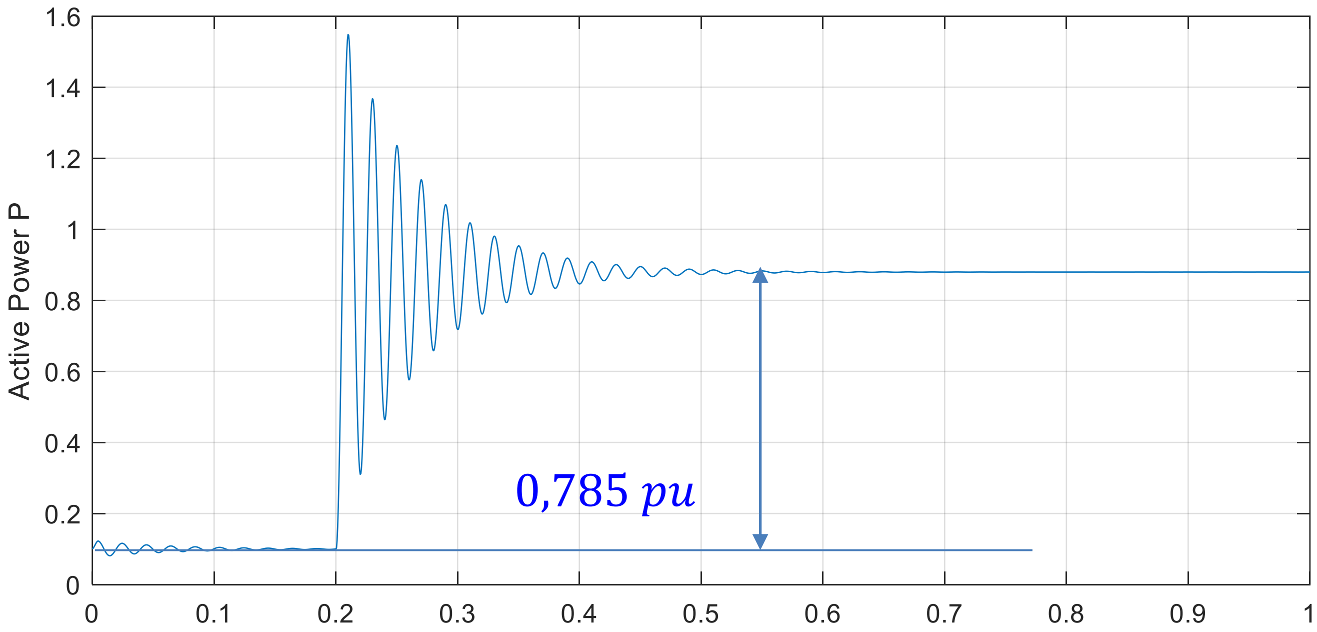
$\Delta\delta_m = \pi/20$

$\Delta P = 0{,}785\ pu$

The steady state model is correct but the dynamics of the simulated system induces a poorly damped poles

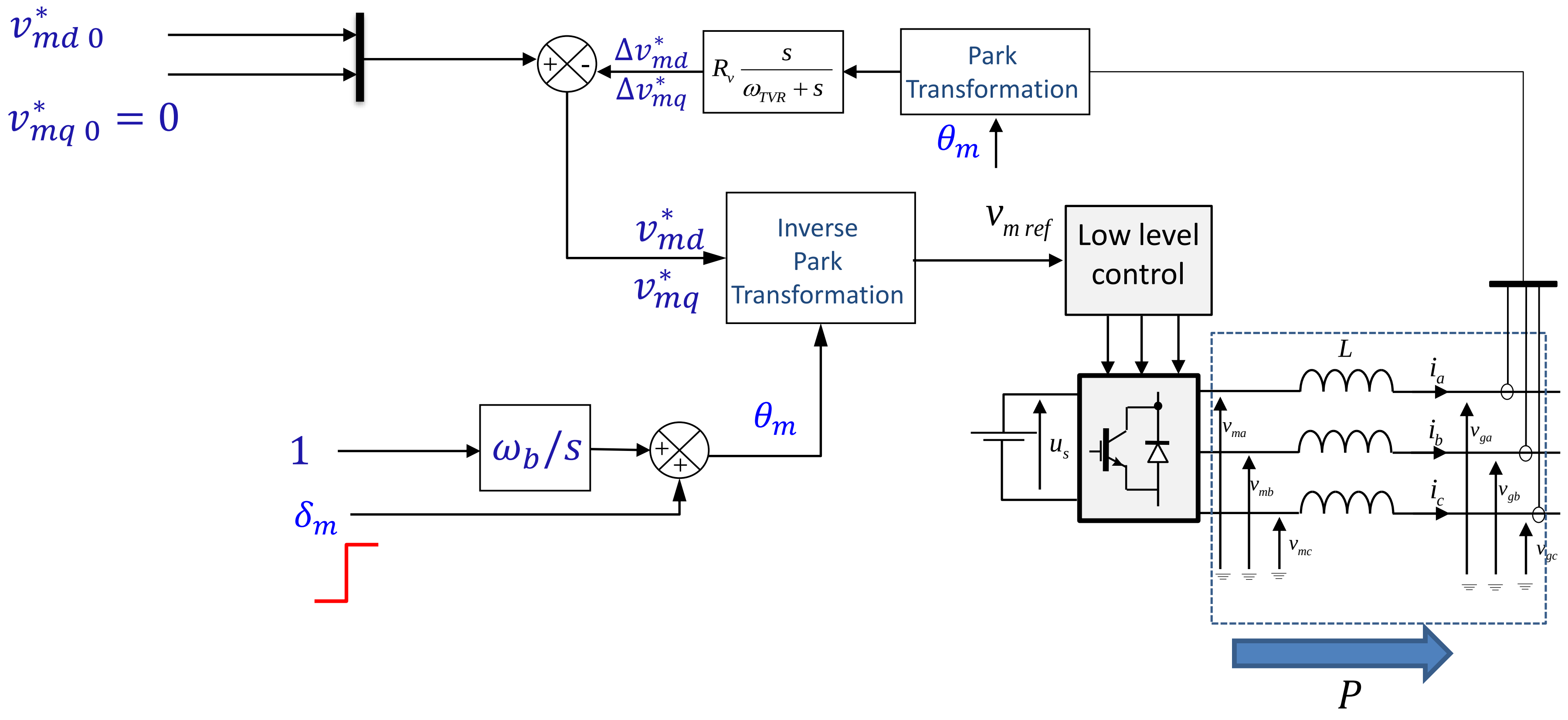
It can be demonstrated that :

$$\Delta P \approx \frac{V_g V_m}{X} \frac{1}{\left(R + \frac{L}{\omega_b} s\right)^2 + (L\omega_b)^2} \Delta\delta_m$$



In transmission system $R_c \ll L_c\omega_g$

It is possible to damp this system by adding a damping resistance thanks to the control



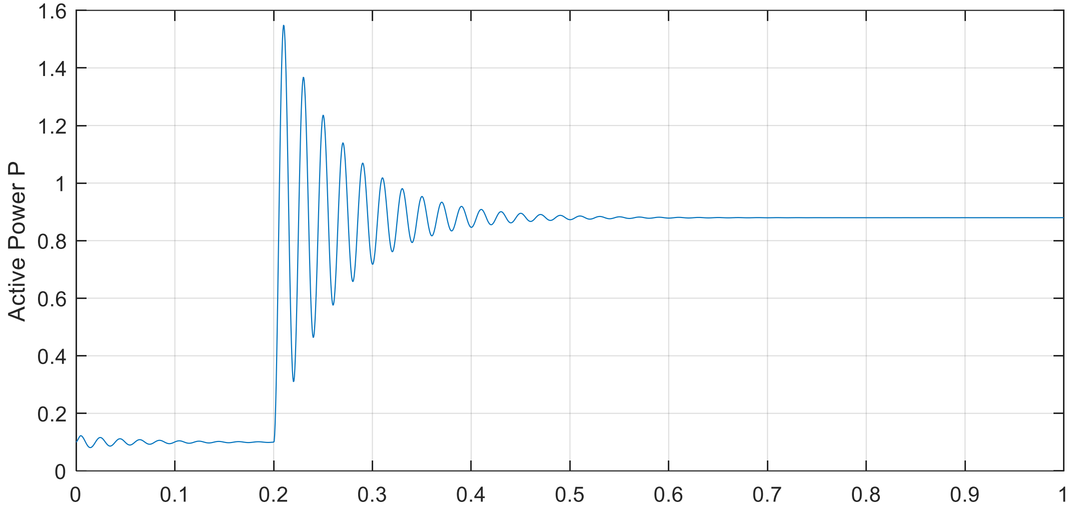
A virtual damping resistance is introduced in the control

$$\Delta v^*_{md} = R_v i_{gd} \qquad \Delta v^*_{mq} = R_v i_{gq}$$

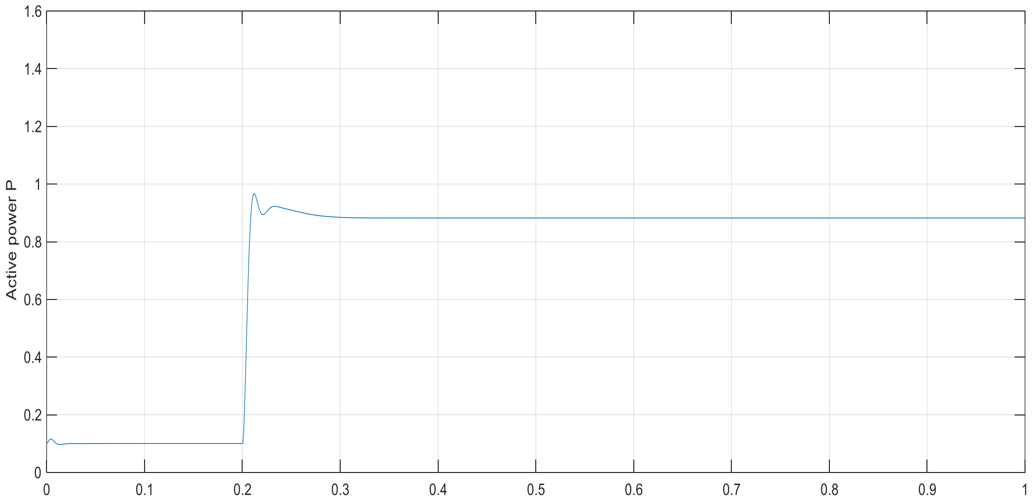
To cancel its effect in steady state, a washout filter is added

$$\Delta v^*_{md} = \frac{s}{\omega_{TVR}+s} R_v i_{gd} \qquad \Delta v^*_{mq} = \frac{s}{\omega_{TVR}+s} R_v i_{gq}$$

Without damping resistance



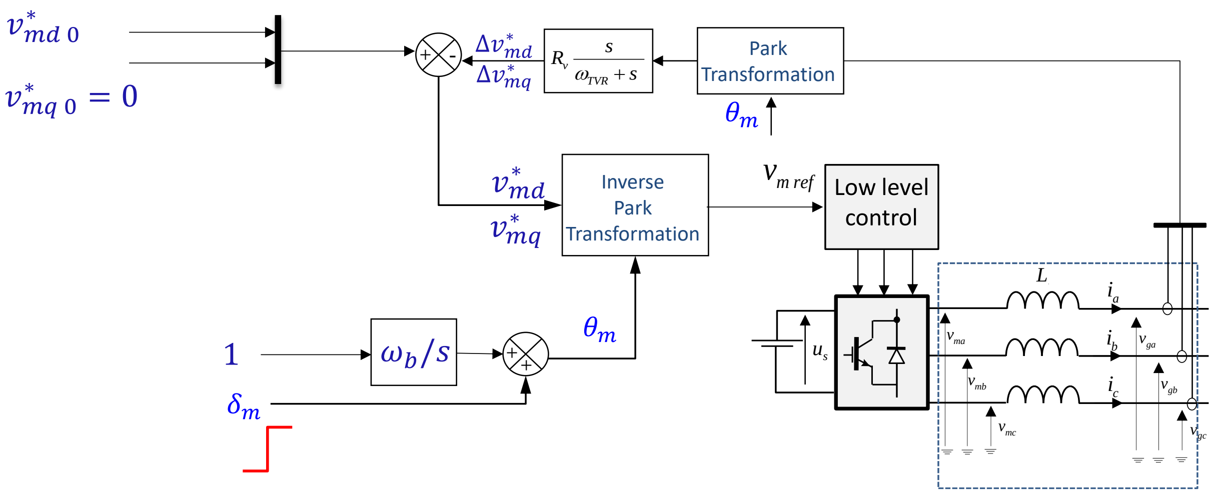
With damping resistance



The system with the a damping resistance behaves nearly as the quasi static system since the oscillatory poles are damped

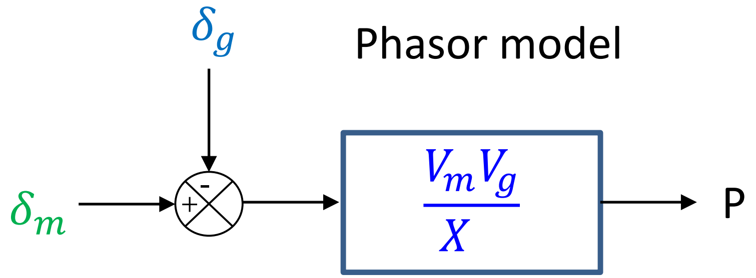
In the following slides, only the quasi static model will be used

Dynamic model

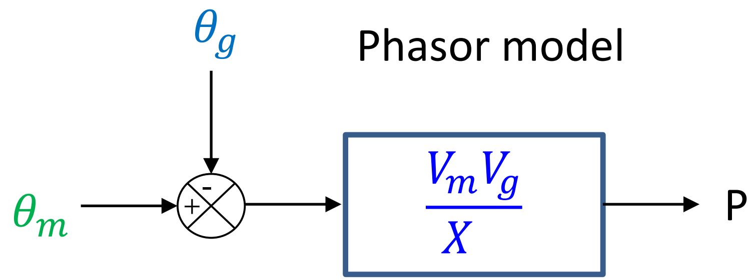


Simplified model for active power

Phasor model

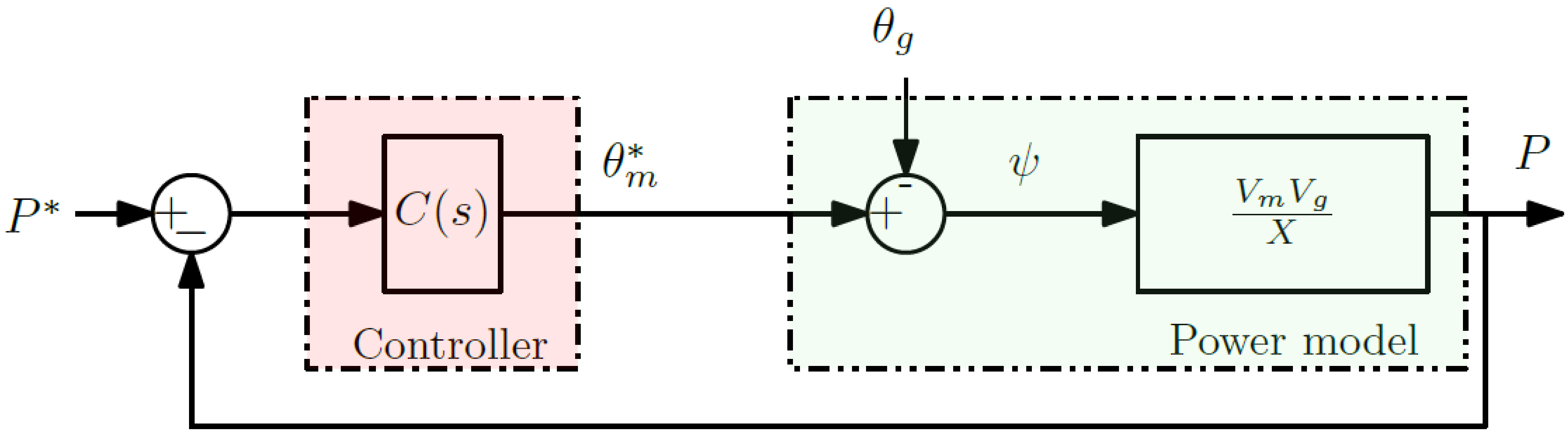


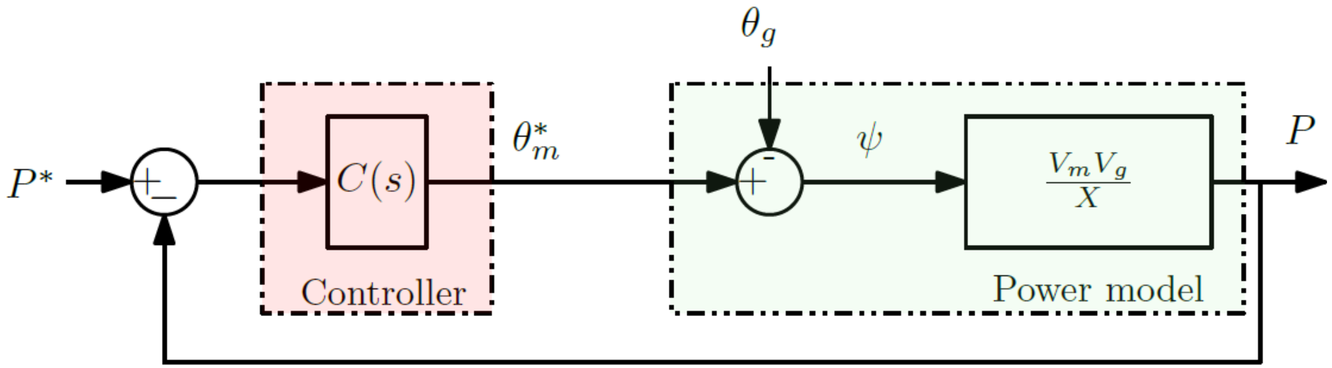
Phasor model



L. Zhang, L. Harnefors, and H. Nee, “Power-Synchronization Control of Grid-Connected Voltage-Source Converters,” *IEEE Trans. Power Syst.*, vol. 25, no. 2, pp. 809–820, May 2010,

In order to control the active power a closed loop system is required





If this loop is stable,

P is constant in steady state

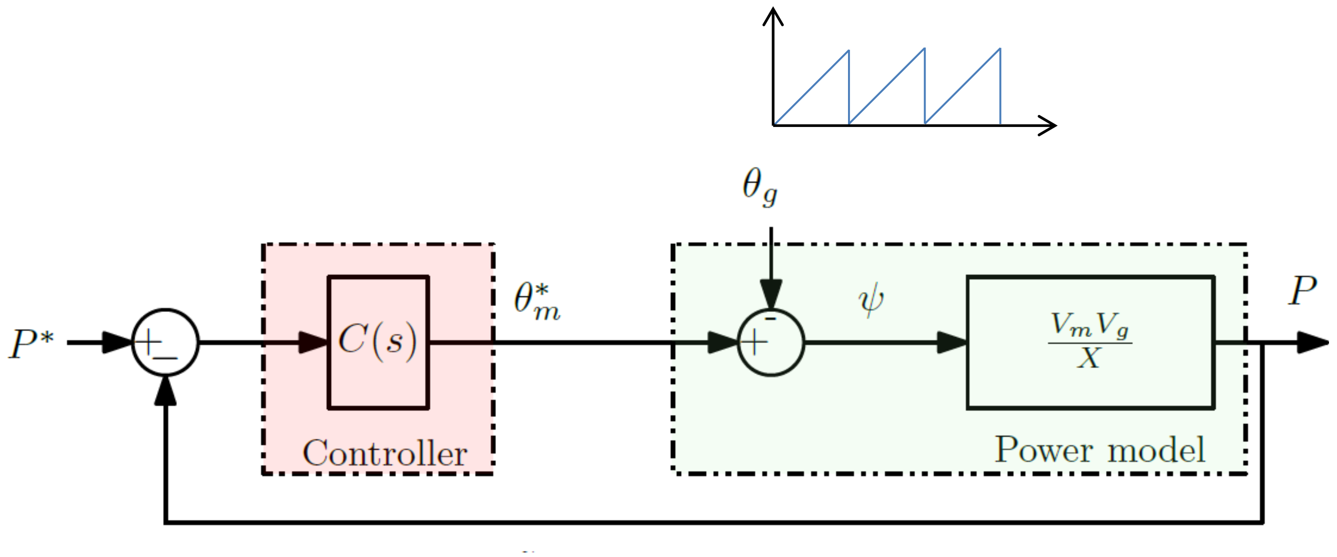
$\theta_m - \theta_g$ is constant in steady state :

The VSC is synchronized to the AC network

There is an inherent relation between the *active power control and the synchronization*

This can be considered as a characteristic of the grid-forming control

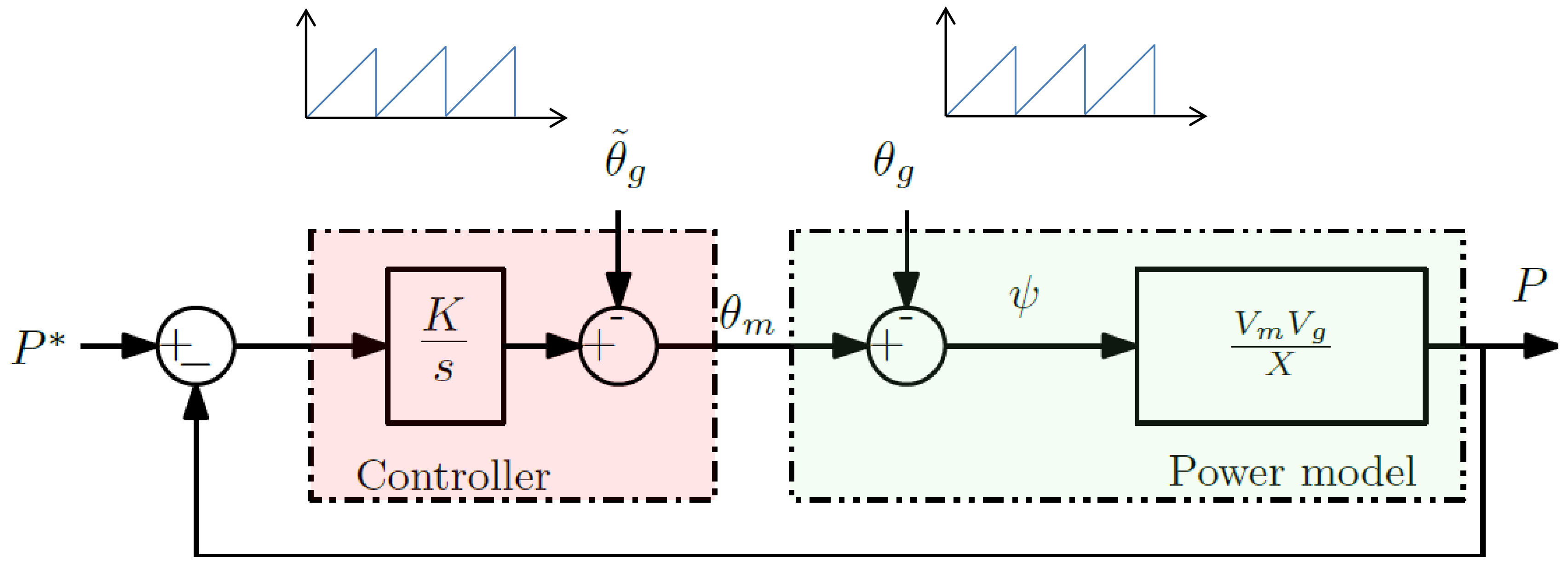
An external synchonization (eg. PLL) algorithm is not compulsory which doesn’t mean that it can’t be usefull.



The different variants on the grid forming control depends on the requirements which are asked for this control.

First requirement : $P = P^*$ in steady state

An integral action is needed in the controller, but it is not sufficient due to θ_g which represents a linear disturbance.

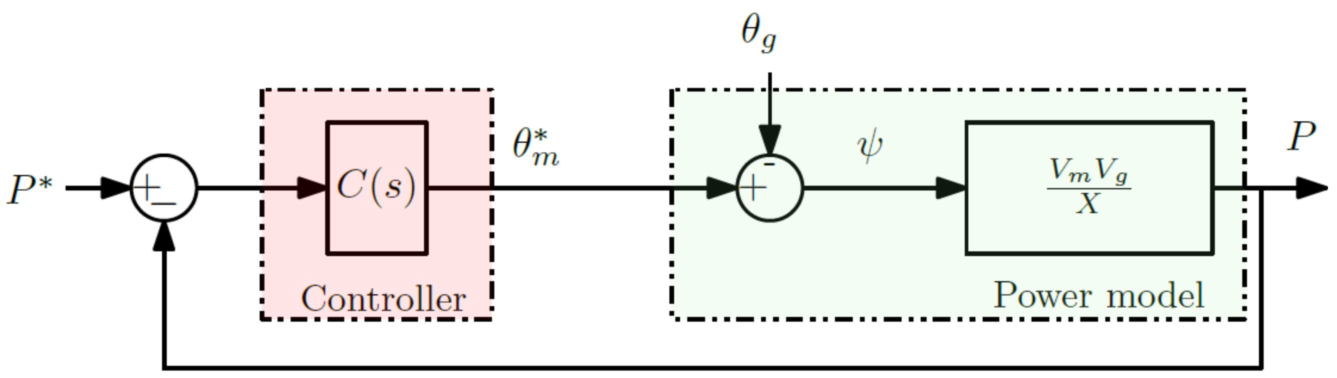


For the active power control, the grid angle θ_g represents a disturbance.

It can be compensated in the control thanks to a grid angle estimate : $\tilde{\theta}_g$

Thanks to the integral $P = P^*$ in steady state

In this control, a PLL is needed for the grid angle estimation but it has no link with the synchronization process

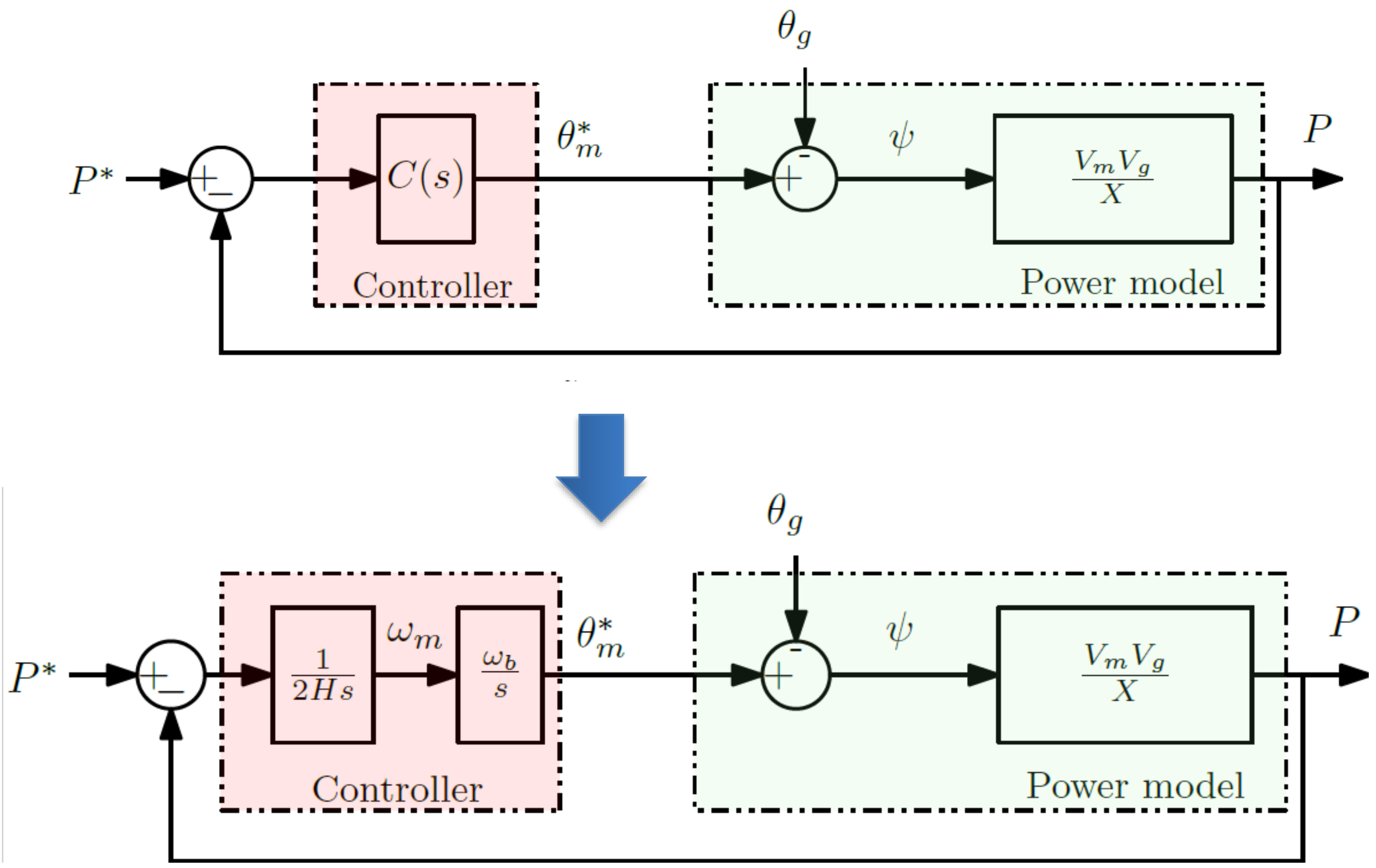


Second requirement : inertial effect

In mechanical systems, the inertial effect, is linked with the storage of kinetic energy

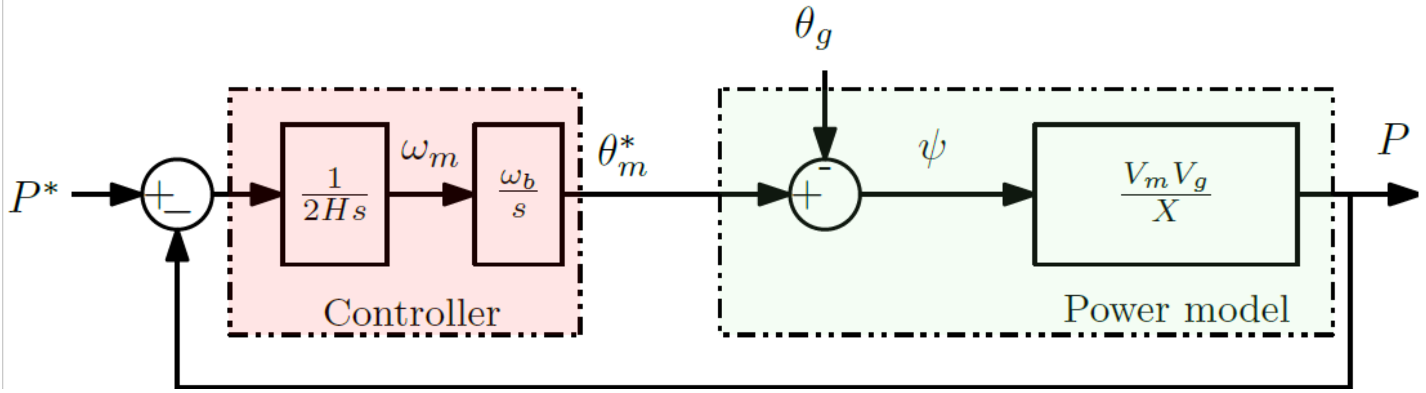
$$\Delta P_{meca} = 2\ H\ \frac{d\omega}{dt} = \frac{2\ H}{\omega_b}\ \frac{d^2\theta}{dt^2}$$

In the power converters, it is ***possible to mimic this inertial effect*** by creating a link between the active power and the second derivative of an angle thanks to the control



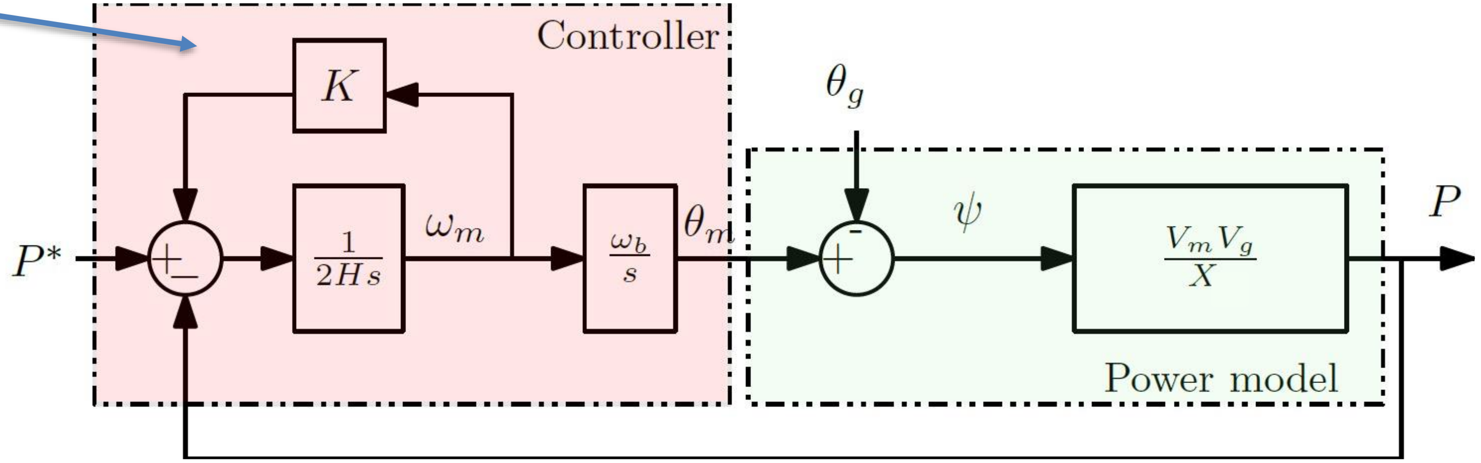
$$\Delta P = 2\,H\,\frac{d\omega_{\,m}}{dt} = \frac{2\,H}{\omega_b}\,\frac{d^2\theta_m}{dt^2}$$

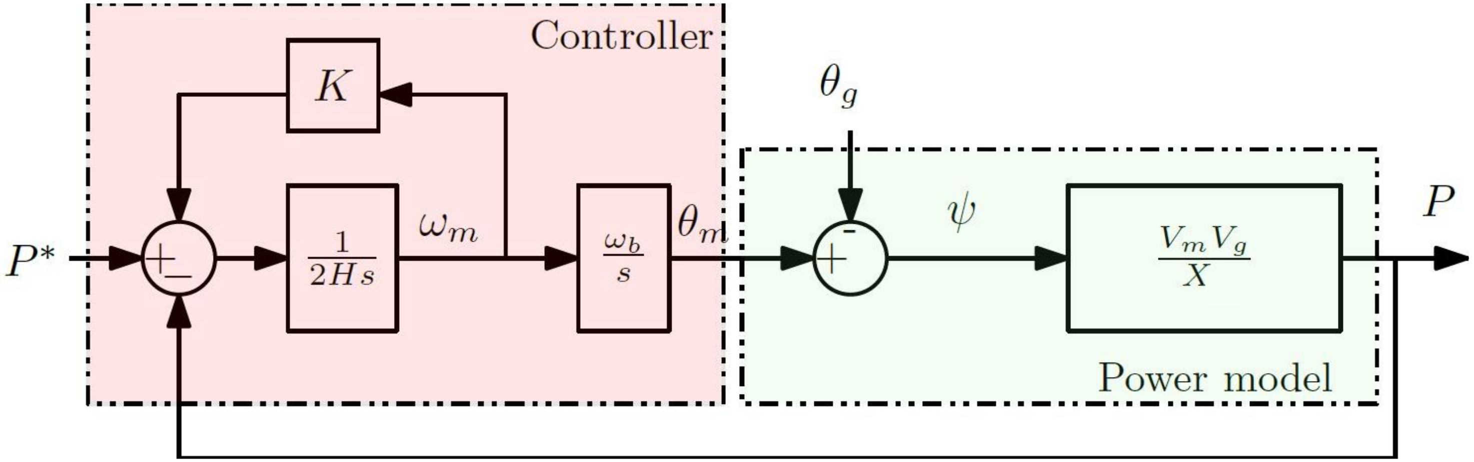
With the double integrator, no need to add grid angle compensation



This a second order system with a null damping. Several solutions exist to stabilize this loop. One solution is to add a damping effect

Damping effect





In steady state $\omega_m = \omega_g$, the grid frequency

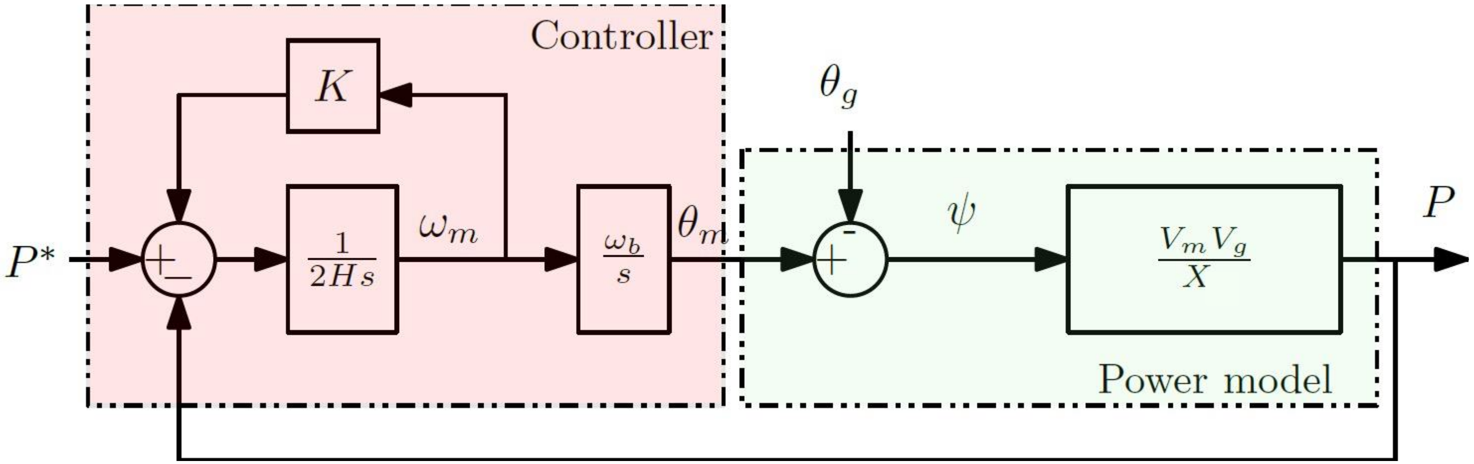
$\Delta P = 0 = P^* - P - K\omega_g \Rightarrow P = P^* - K\omega_g$

In steady state P^* may be different from P

With this topology of control, it exists several solutions to solve this issue

Among them, the so-called VSM

$\widetilde{\omega_g}$: Estimate of the grid frequency



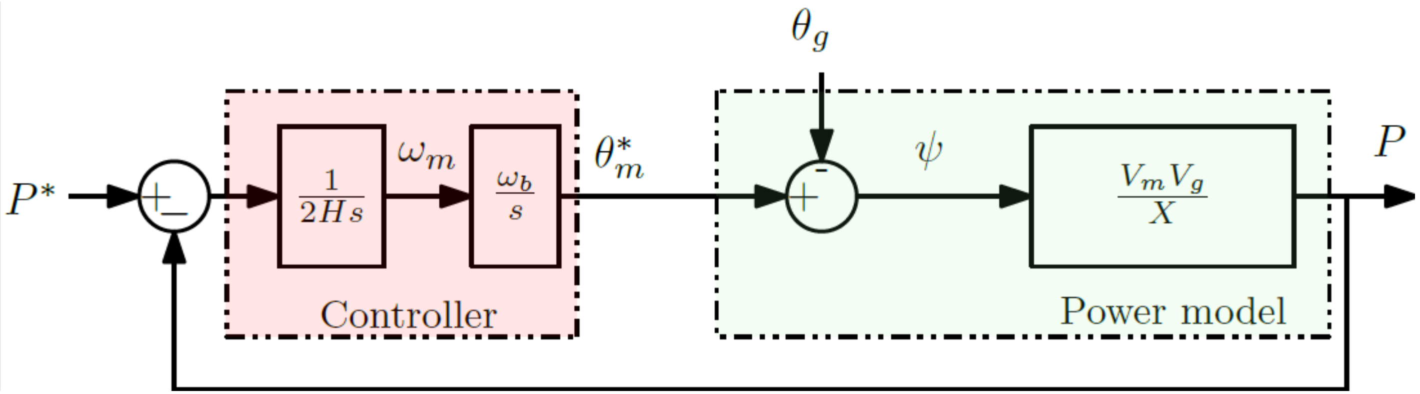
In steady state $\omega_m = \omega_g$, the grid frequency

$$\Delta P = 0 = P^* - P - K\left(\omega_g - \widetilde{\omega_g}\right)$$

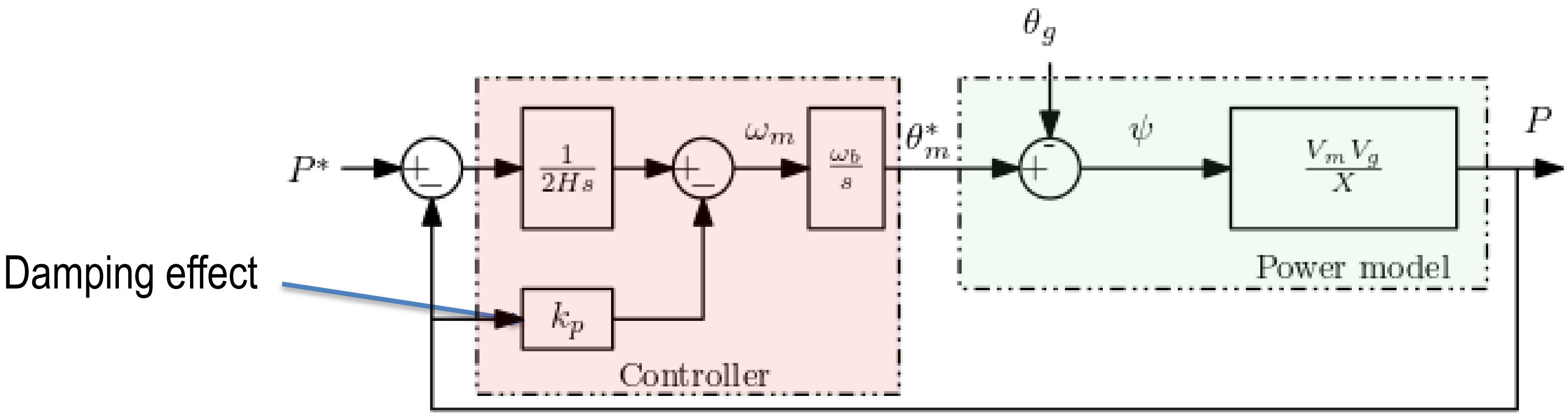
$$\omega_g = \widetilde{\omega_g}$$

Then $P^* = P$

This supposes to use a PLL in order to estimate the grid frequency

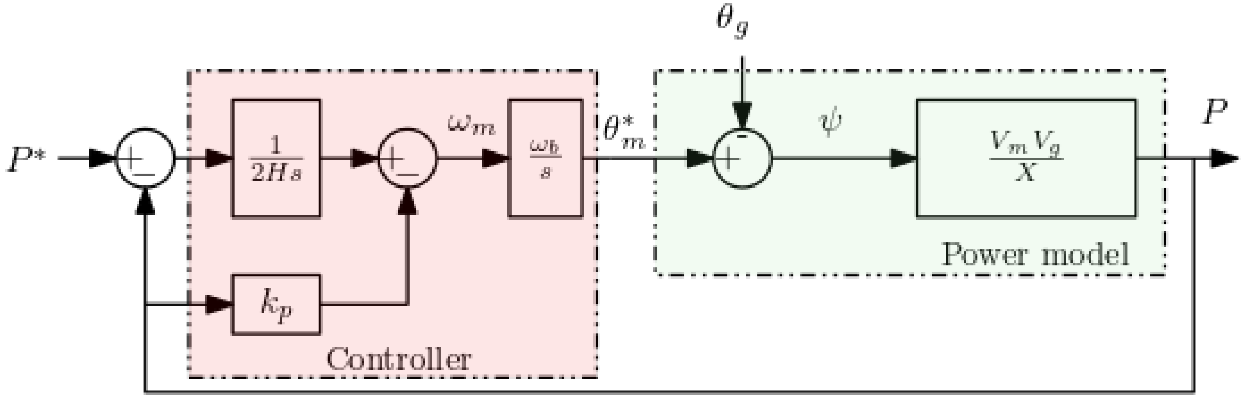


Another solution to damp the closed loop system is to **add a proportionnal action on the active power.**



No PLL is required for this control.

In the following slides, only this control will be studied



Assumption : V_m= V_g=1

$$P = \frac{1}{\frac{2HX}{\omega_b}s^2 + 2Hk_p s + 1} P^* - \frac{\frac{2H}{\omega_b}s^2}{\frac{2HX}{\omega_b}s^2 + 2Hk_p s + 1}\theta_g$$

θ_g**,** the disturbance is cancelled by the double integrator included in the control.

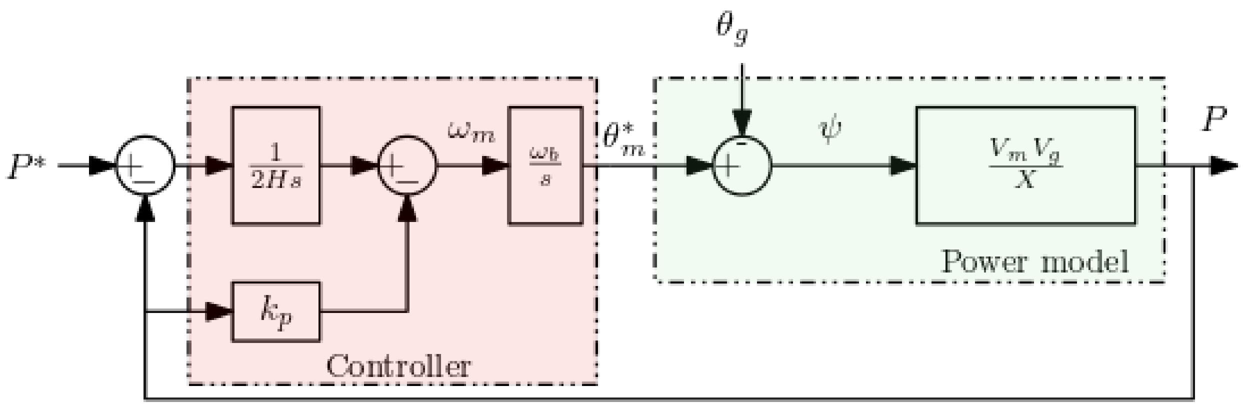
Characteristic polynomial : $P_c(s) = \frac{2HX}{\omega_b}s^2 + 2Hk_p s + 1 = \frac{s^2}{\omega_n^2} + \frac{2\xi}{\omega_n}s + 1$

$$\omega_n = \sqrt{\frac{\omega_b}{2HX}} \qquad \xi = \mathrm{k_p}\sqrt{\frac{H\omega_b}{2X}}$$

For a given value of H, it is possible to choose $\mathrm{k_p}$ with respect to a given damping
Assumption : Xg = 0 X = Xc : the connection impedance of the converter

$$\mathrm{k_p} = \xi\sqrt{\frac{2\boldsymbol{X_c}}{H\omega_b}}$$

The response time cannot be choosen in the same time.

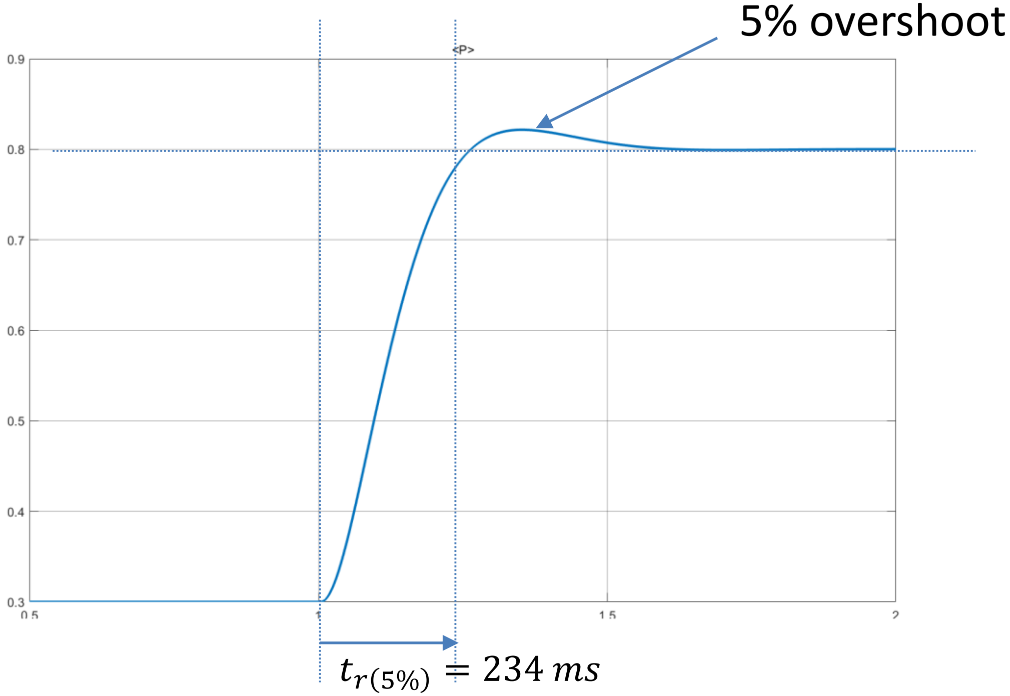


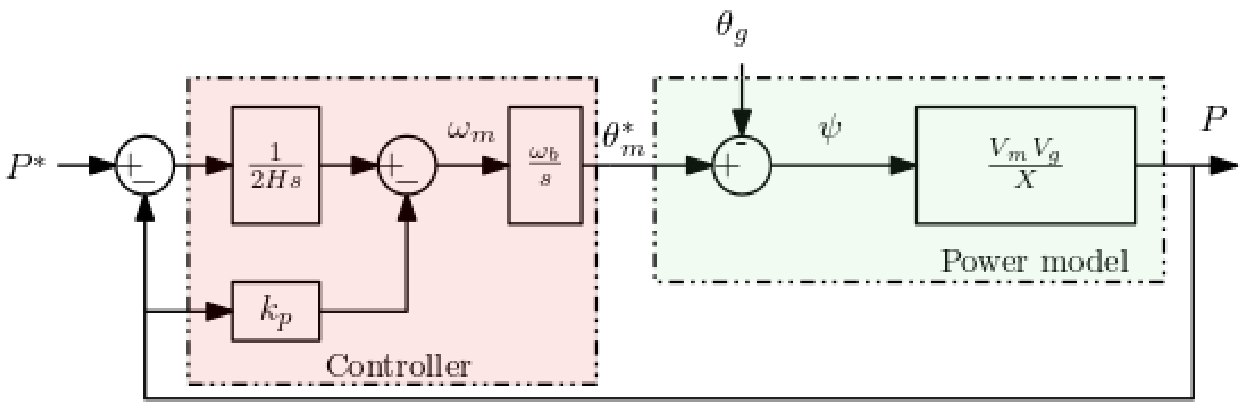
Numerical application : $X_c = 0{,}15$ pu H = 5s $\xi = 0{,}7$

k_p=0,0097 $\omega_n = 14.4\, rad/s$

With a 5% $\xi = 0{,}7$ damping

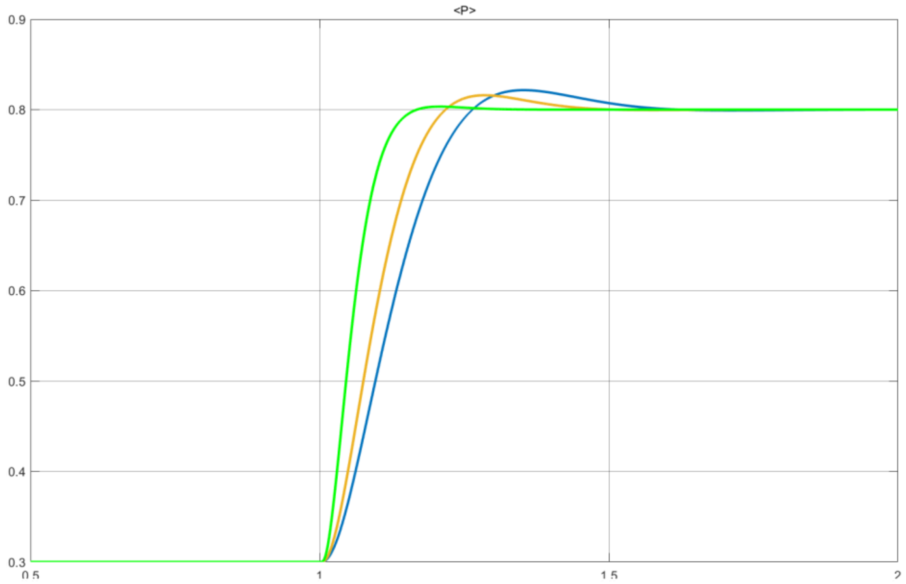
response time $t_{r(5\%)} \approx \frac{3}{\omega_n} = 3\sqrt{\frac{2HX}{\omega_b}}$ = 200 ms





Response time for different values of H

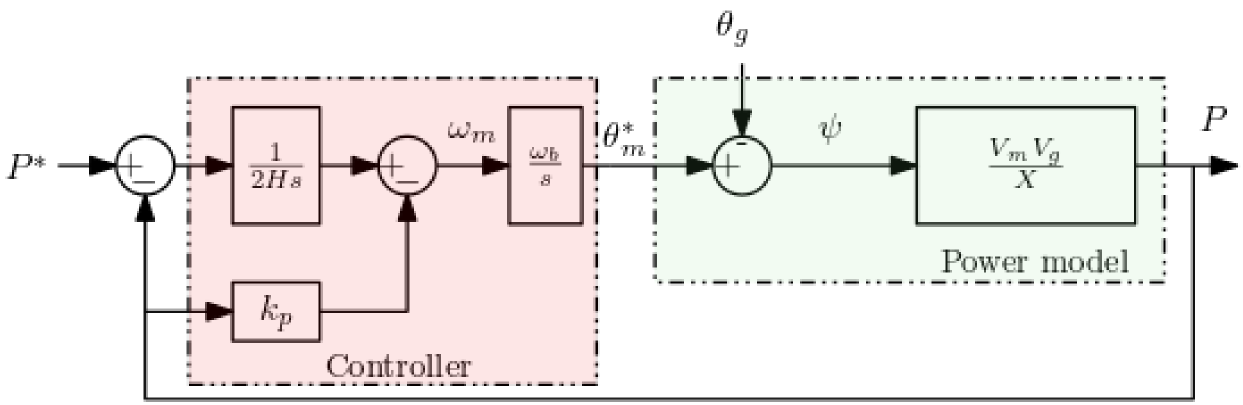
$$t_{r(5\%)} \approx \frac{3}{\omega_n} = 3\sqrt{\frac{2HX}{\omega_b}} = 3\sqrt{\frac{2H(X_c+X_g)}{\omega_b}}$$



$$t_{r(5\%)} = 234\ ms$$

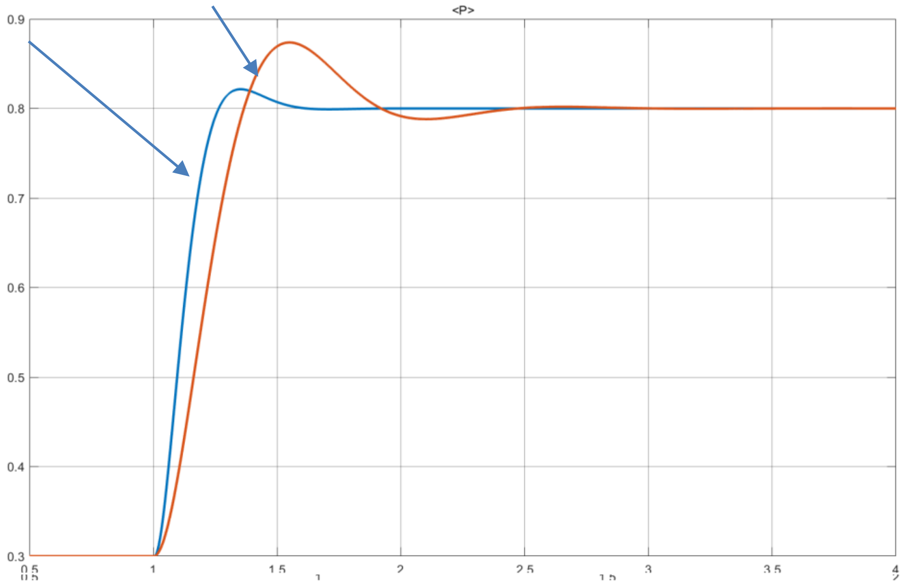
As expected the response time is decreasing

The overshoot is slightly different but stays in an acceptable range of variation



SCR = 20

SCR = 2



$t_{r(5\%)} = 234\,ms$

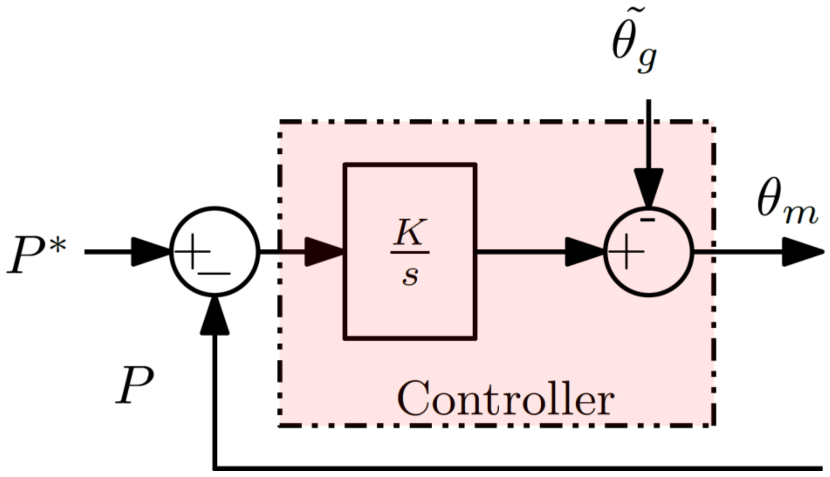
Dynamics for different SCR

With SCR = 2, the grid impedance X_g is ten time higher than when SCR = 20

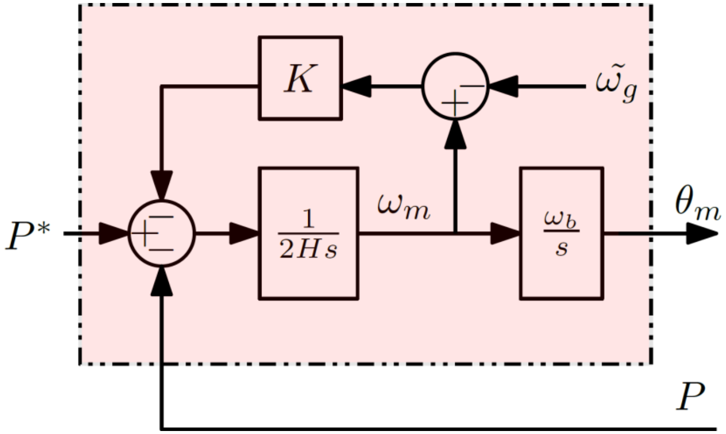
The natural frequency and the the damping are decreasing but the behaviour is still acceptable.

$$\omega_n = \sqrt{\frac{\omega_b}{2H(X_g + X_c)}} \qquad \xi \approx k_p \sqrt{\frac{H\omega_b}{2(X_g + X_c)}} = 0{,}34$$

The robustness of the control depends on the connection impedance. In High voltage application 0,15 pu is a typical value, for lower voltage, the connnection impedance is smaller. It is possible to add virtual impedance to keep this robustness property

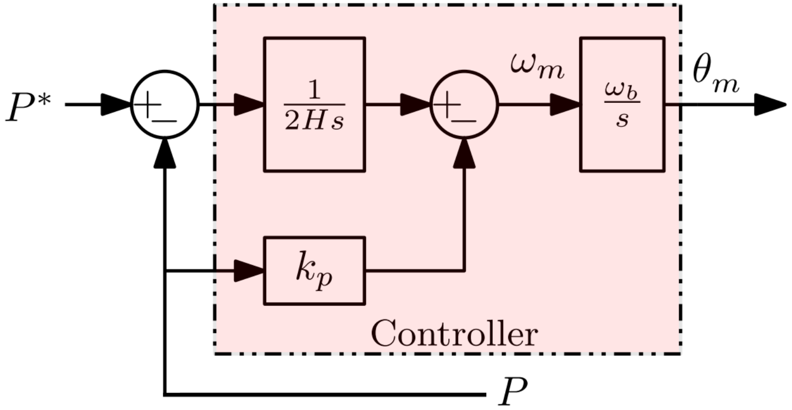


Active power control only



Active power control + inertial effect + frequency estimation

VSM



Active power control + inertial effect

PI controller

Many variants can be deduced from these 3 types of control but, **in case of high voltage applications**, the fundamental properties are not really very different.

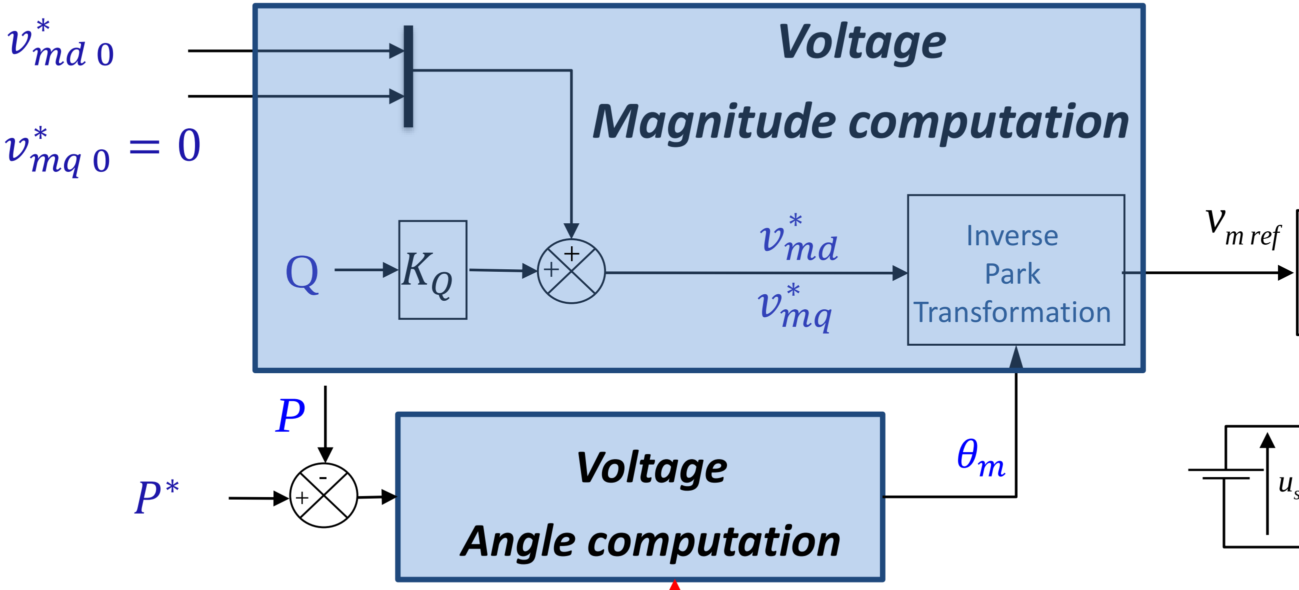
The aim of the controller is to generate a voltage reference in phase and magnitude.

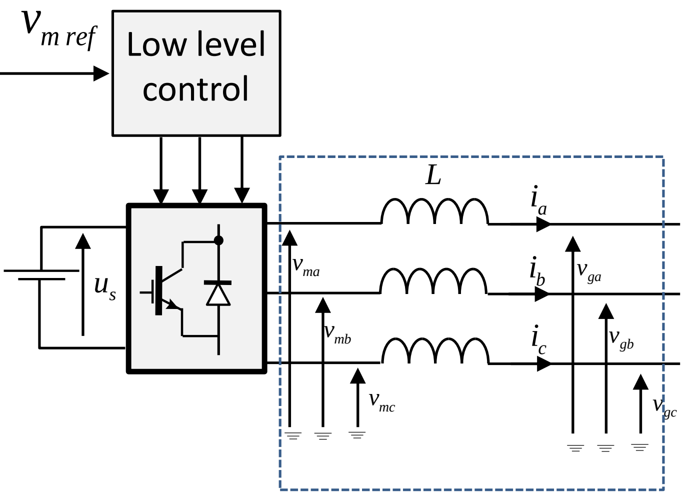
The magnitude voltage computation has to be analyzed.

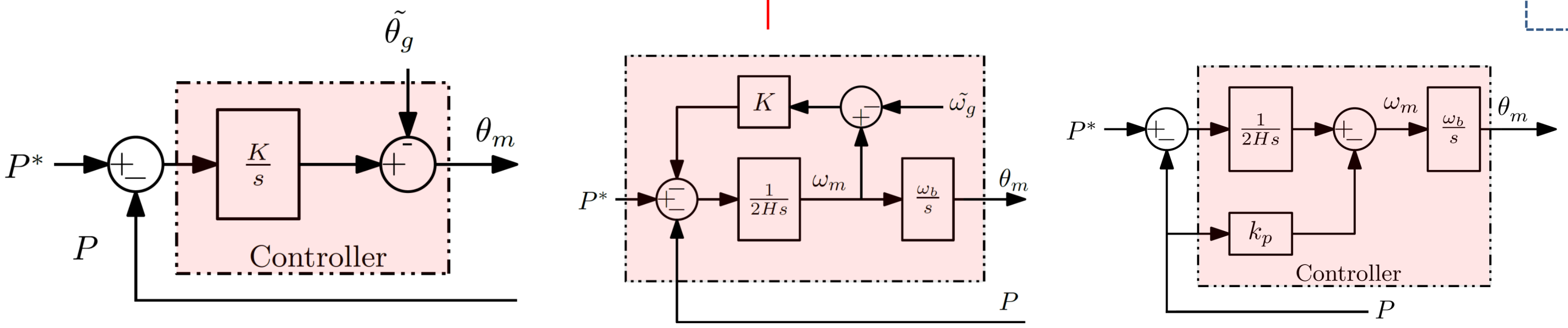
"Classification of Droop-Based Grid-Forming Control Schemes: Application in Forced Commutated Converter-Based HVDC Systems" Electric Power Systems Research (EPSR), ROKROK Ebrahim, **QORIA Taoufik**, BRUYERE Antoine, FRANCOIS Bruno, GUILLAUD Xavier

Since the connection impedance is very small (0.15 pu). No AVR is needed.

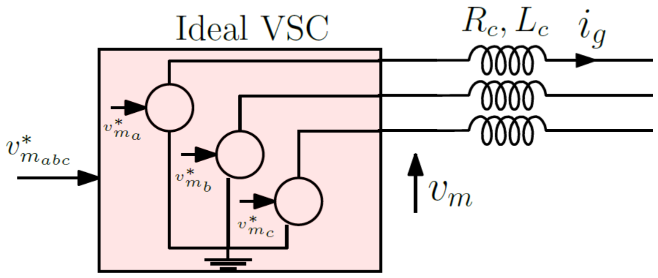
A variation of the voltage magnitude with the reactive power (K_Q) can be added

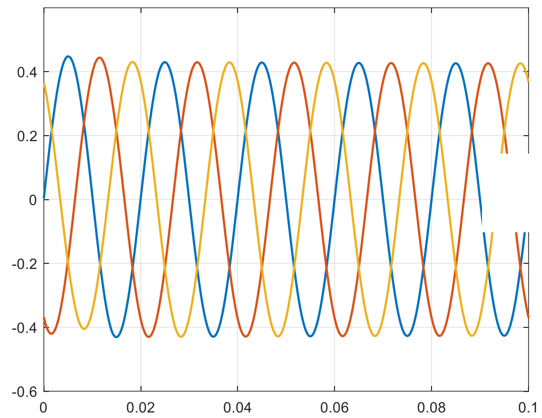






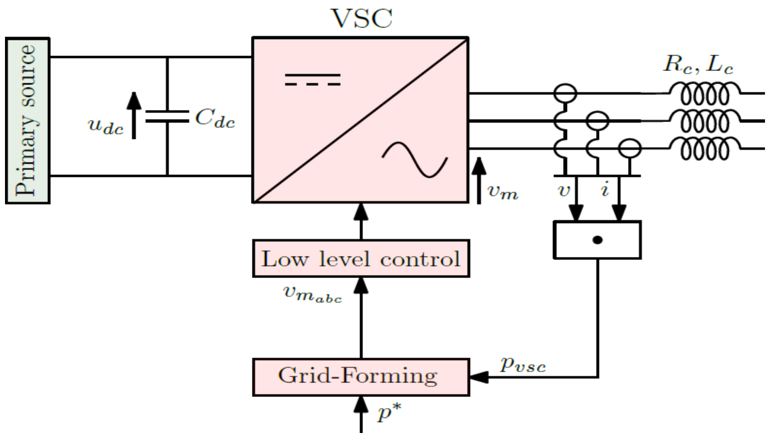
Till now, the power electronic converter has been modelled by a set of three phase ideal voltages.

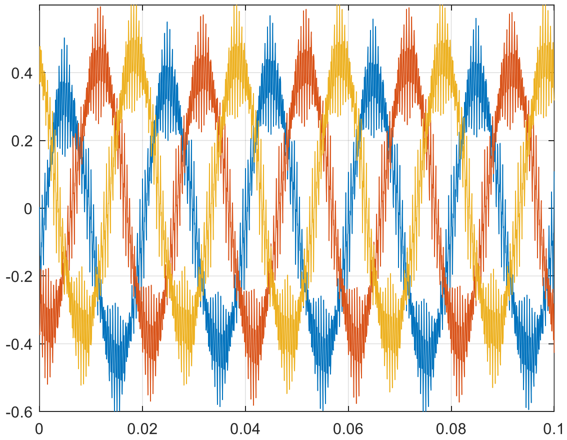




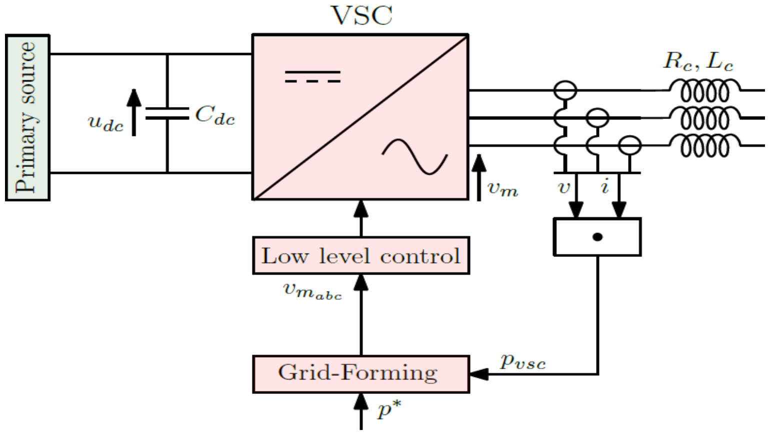
In steady state, the currents are a set of three phase ideal sinusoid

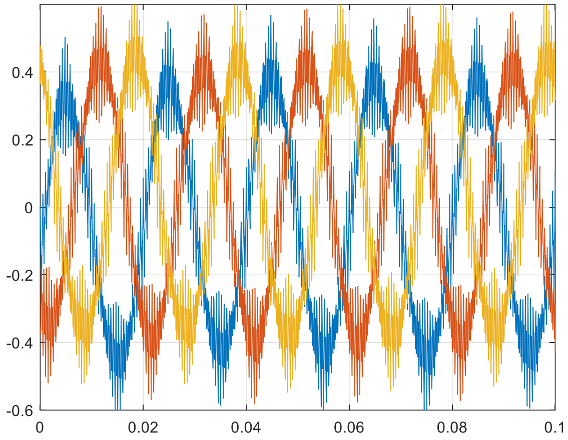
When taking into account the switching of the converter to have a more realistic model, the quality of the grid currents is worsen



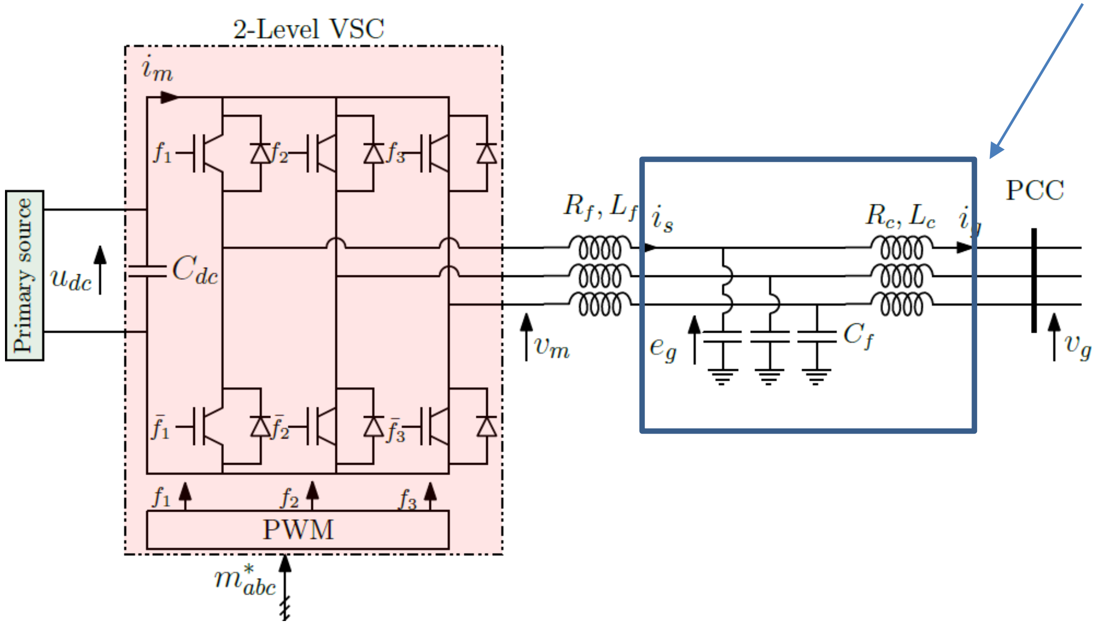


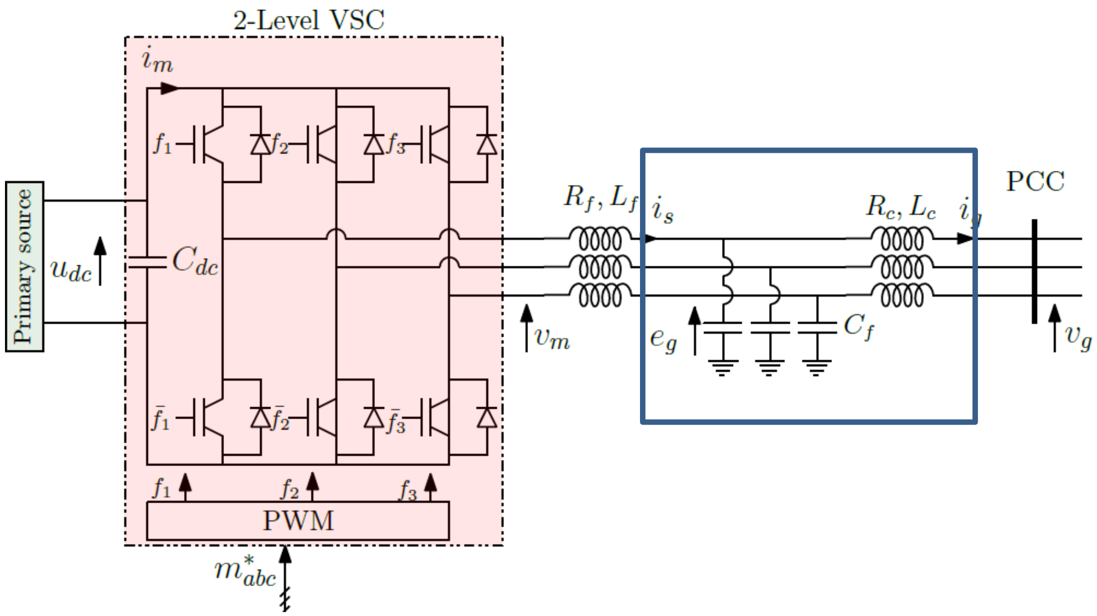
When taking into account the switching of the converter to have a more realistic model, the quality of the grid currents is worsen



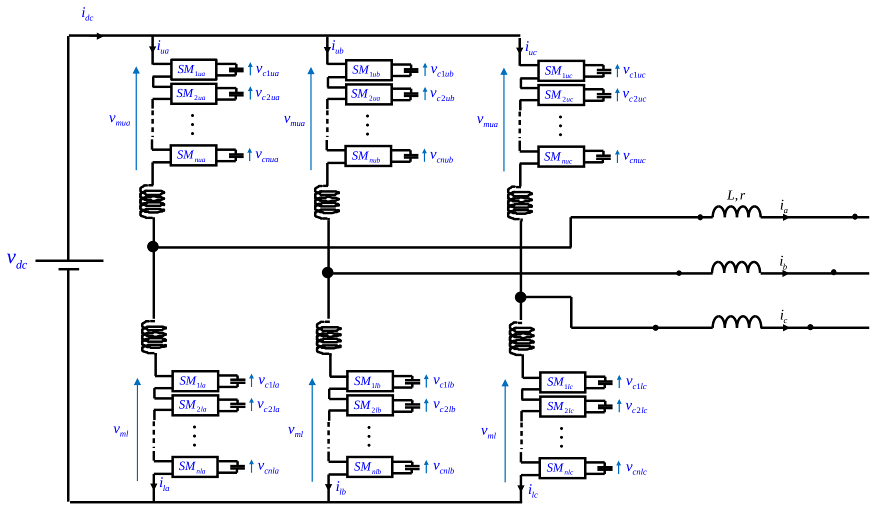


To guarantee the harmonic quality of the grid current, a **LC filter** has to be added





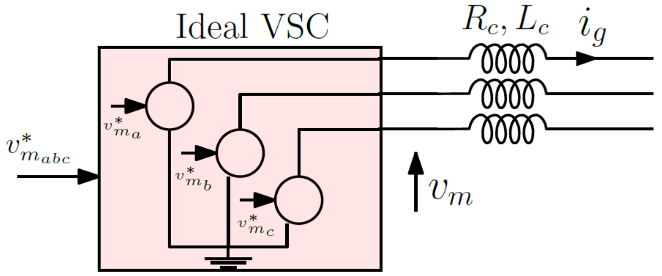
Some control has to be added in order to manage the internal dynamics of the LC filter



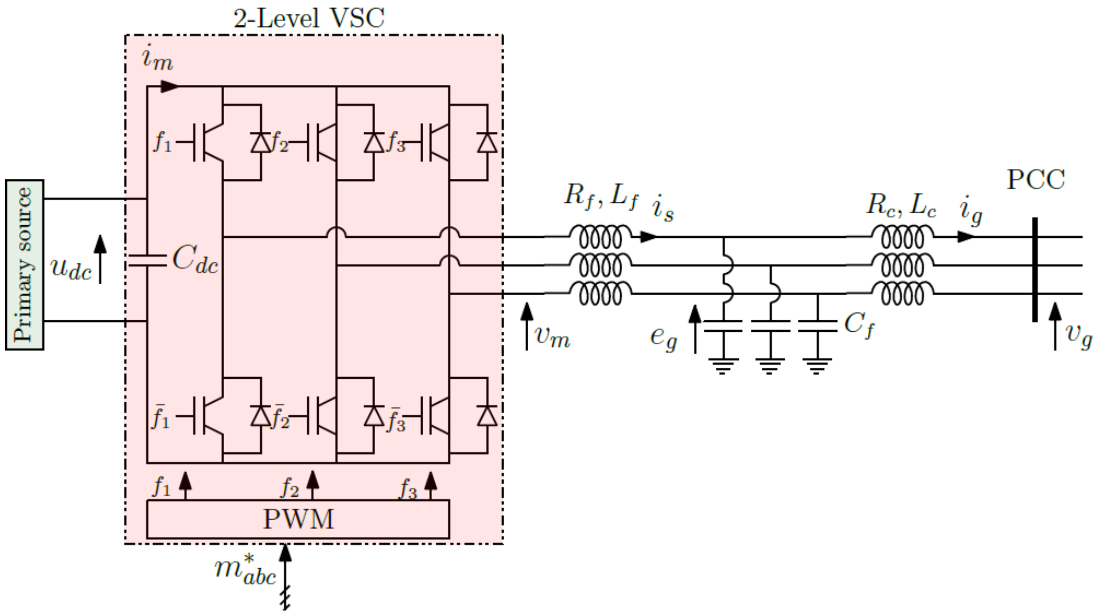
The second solution for the VSC is the MMC topology mainly for large power application

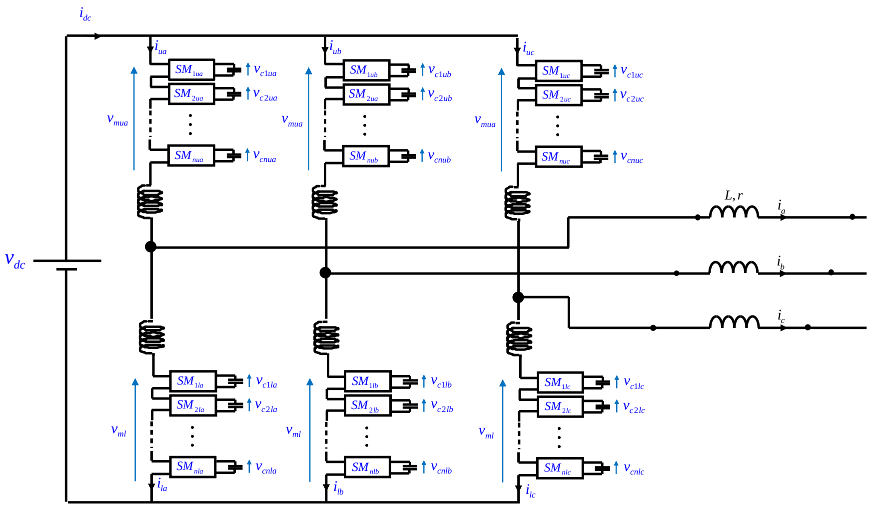
The internal energy has a key role in the overall dynamics of the system

The theory has been developed on this ideal VSC



Is it still valid with these two types of real VSC ?

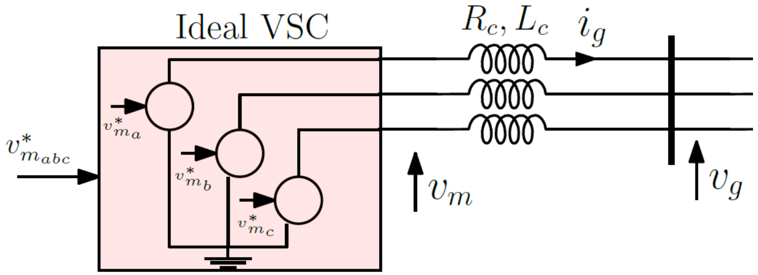




Implementation of the grid-forming converter on a VSC and an MMC

In the ideal VSC, the active power is controlled thanks to angle

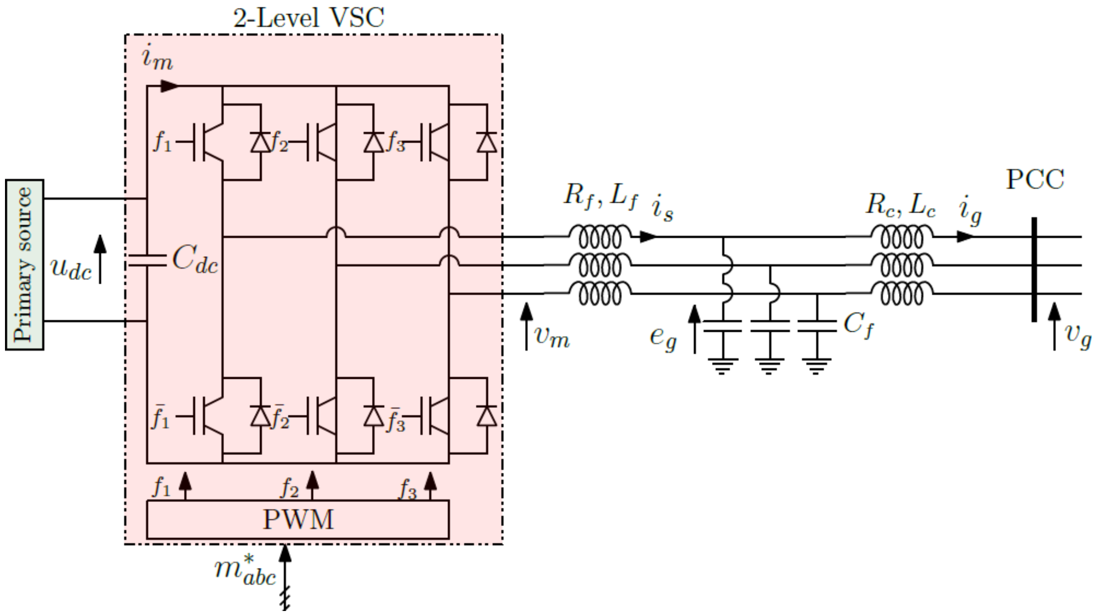
δ_m : angle between v_m and v_g



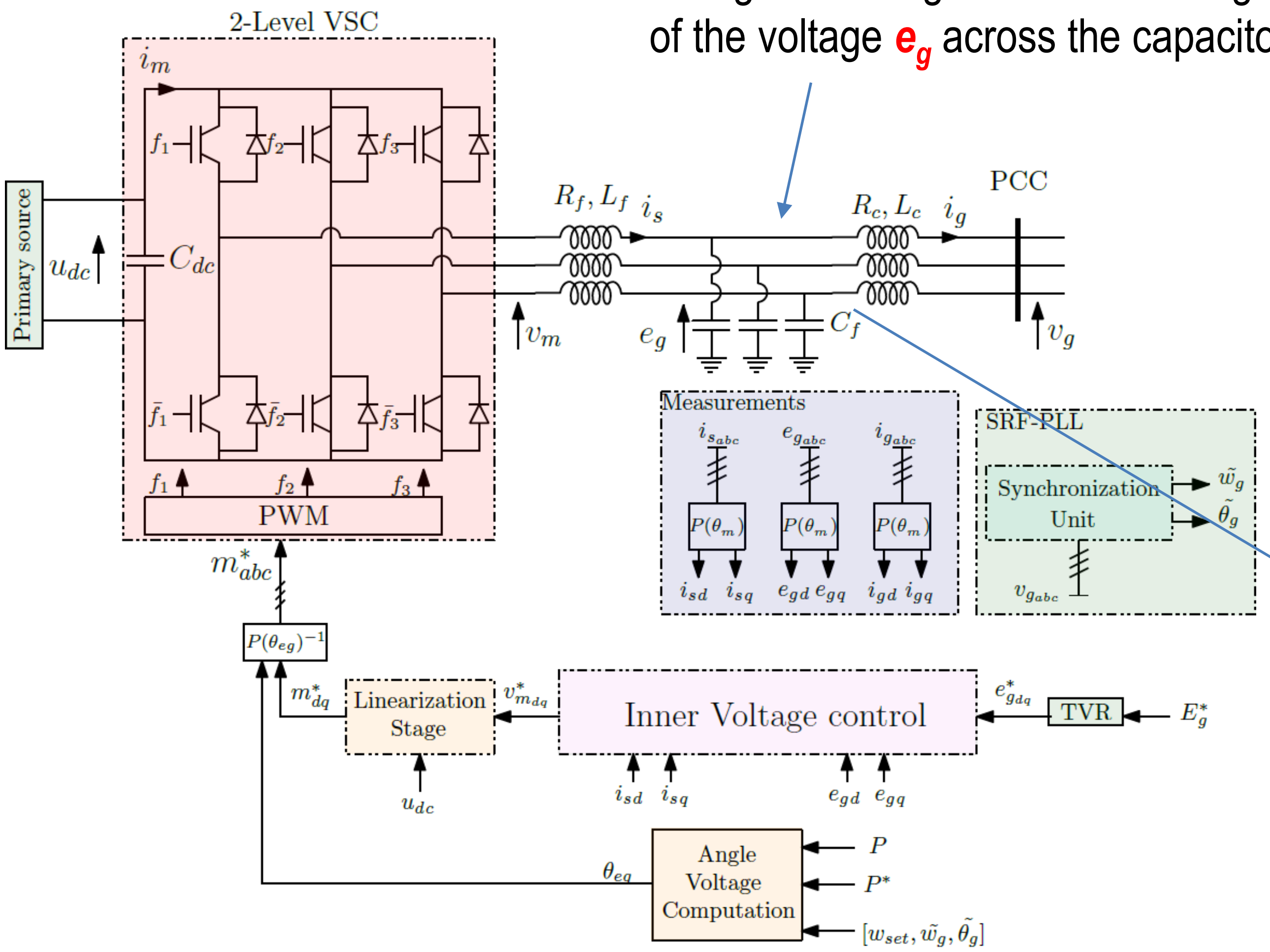
When including the LC filter, the active power is controlled to the angle

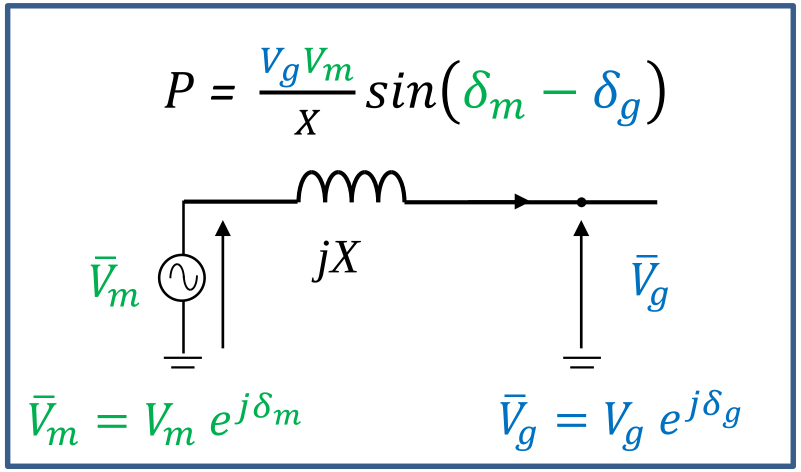
δ_{eg} : angle between e_g and v_g

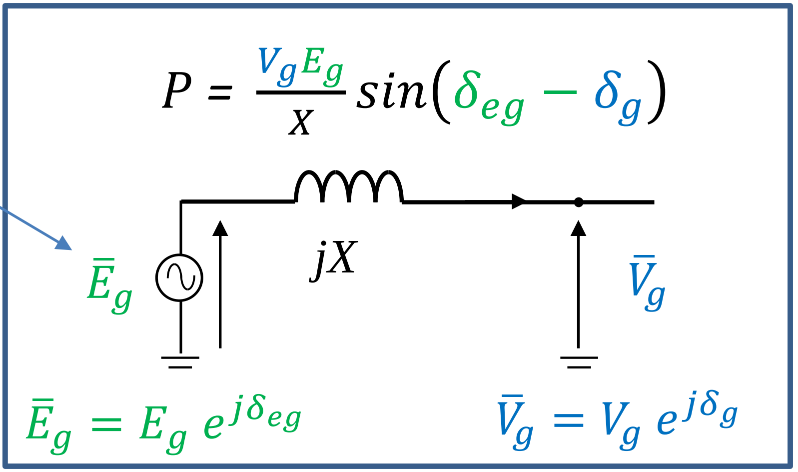
e_g is the voltage across the capacitor C_f.



The grid forming control is driving the angle of the voltage e_g across the capacitor







- The classical control is based on cascaded loop => Drawback: even if it’s possible it’s hard to obtain a general tuning
- Proposition: Direct AC Voltage Control
  - General idea: reversed the quasi-stationary model of the L-Filter

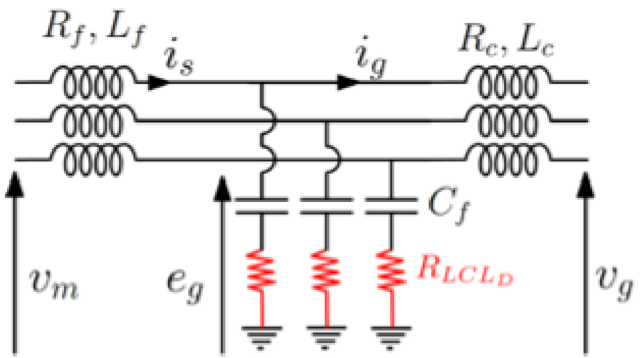
$$v^*_{m_d} = e^*_{g_d} + R_f i_{s_d} - L_f \omega_m i_{s_q}$$

$$v^*_{m_q} = e^*_{g_q} + R_f i_{s_q} + L_f \omega_m i_{s_d}$$

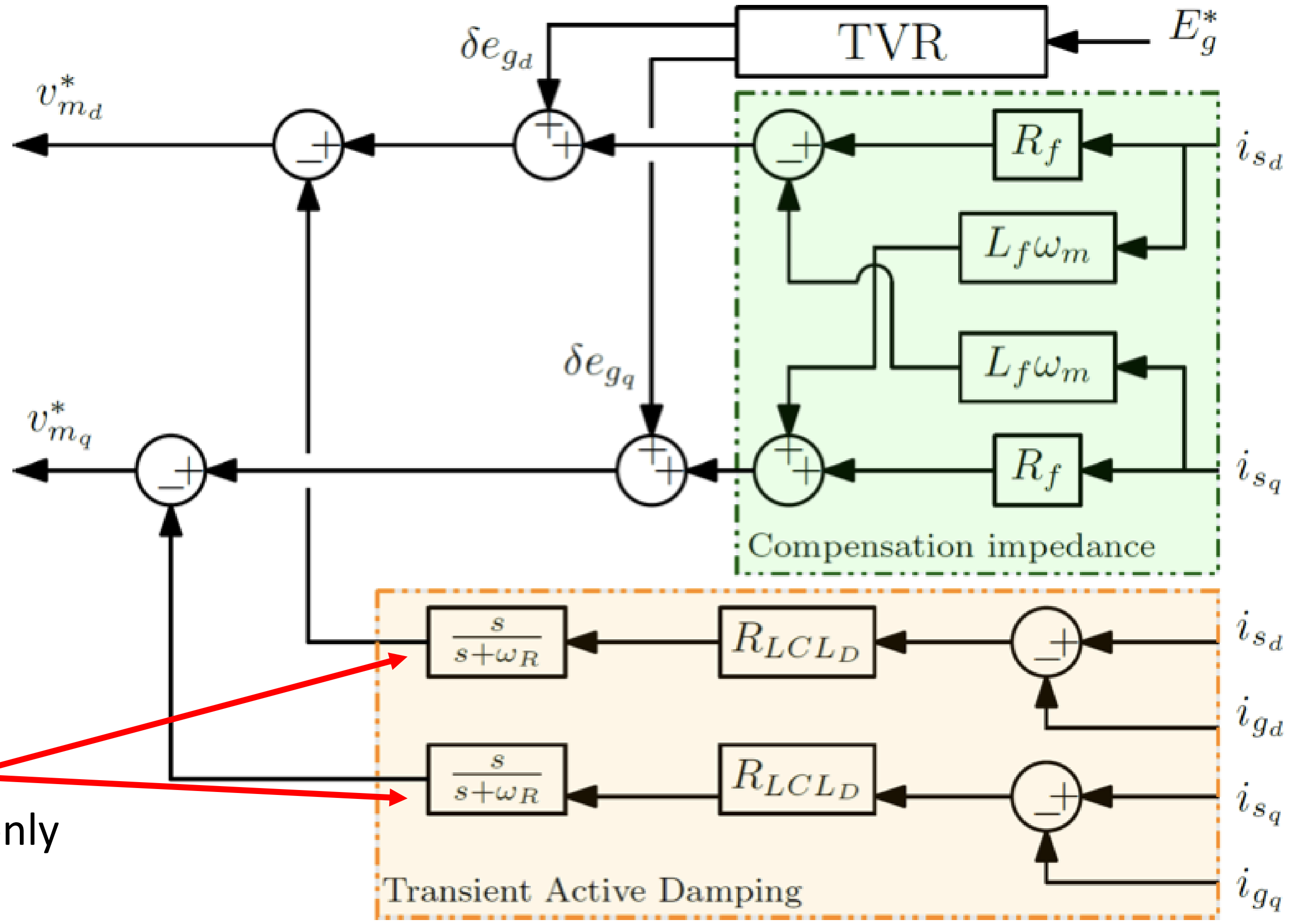
  - And to avoid LCL resonances, add an active damping

$$v^*_{m_d} = R_f i_{s_d} - L_f \omega_m i_{s_q} + e^*_{g_d} - \underbrace{R_{LCL_D}(i_{s_d} - i_{gd})}_{e_{gd}}$$

$$v^*_{mq} = R_f i_{s_q} + L_f \omega_m i_{s_d} + e^*_{g_q} - \underbrace{R_{LCL_D}(i_{s_q} - i_{gq})}_{e_{gq}}$$



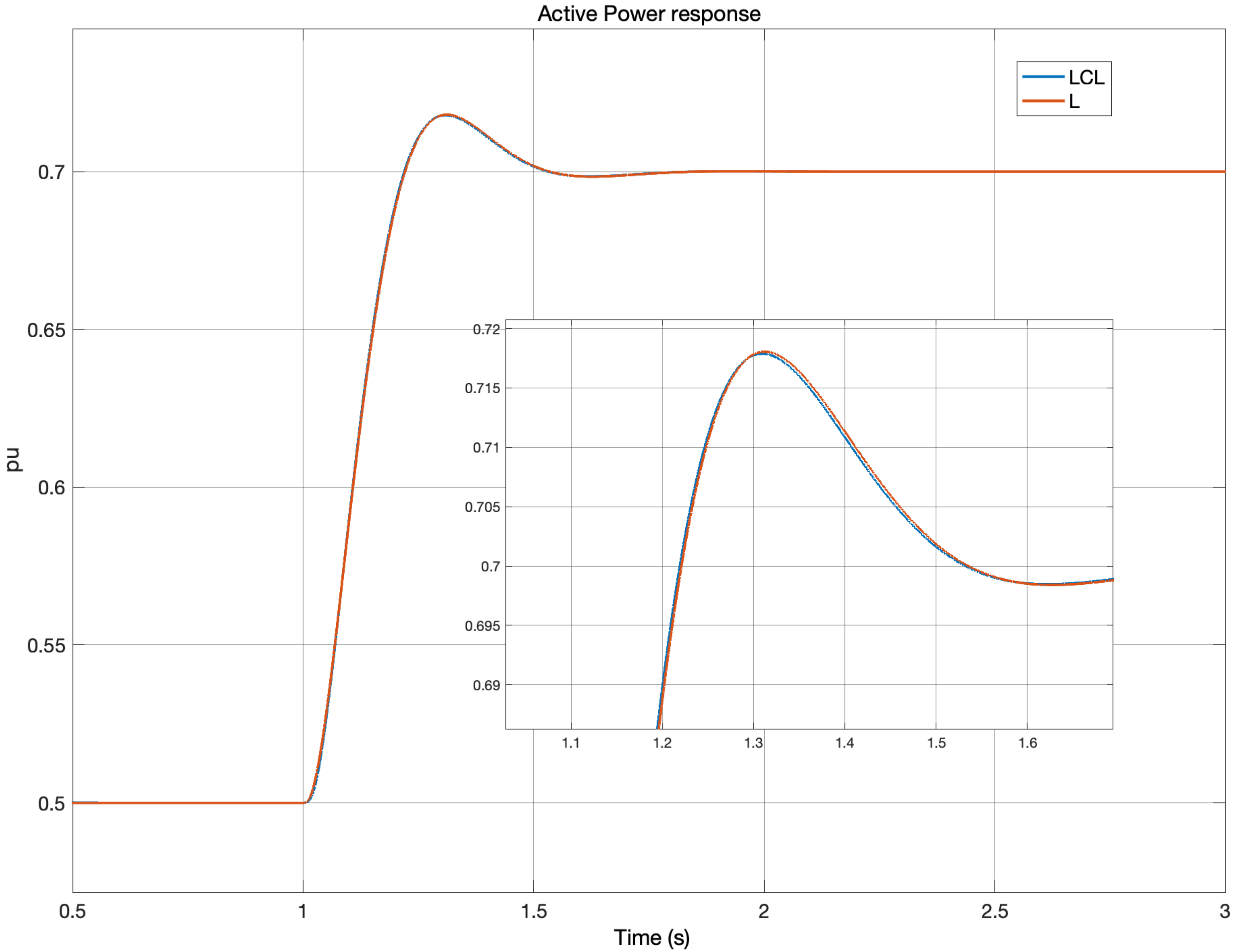
- Control schematic:



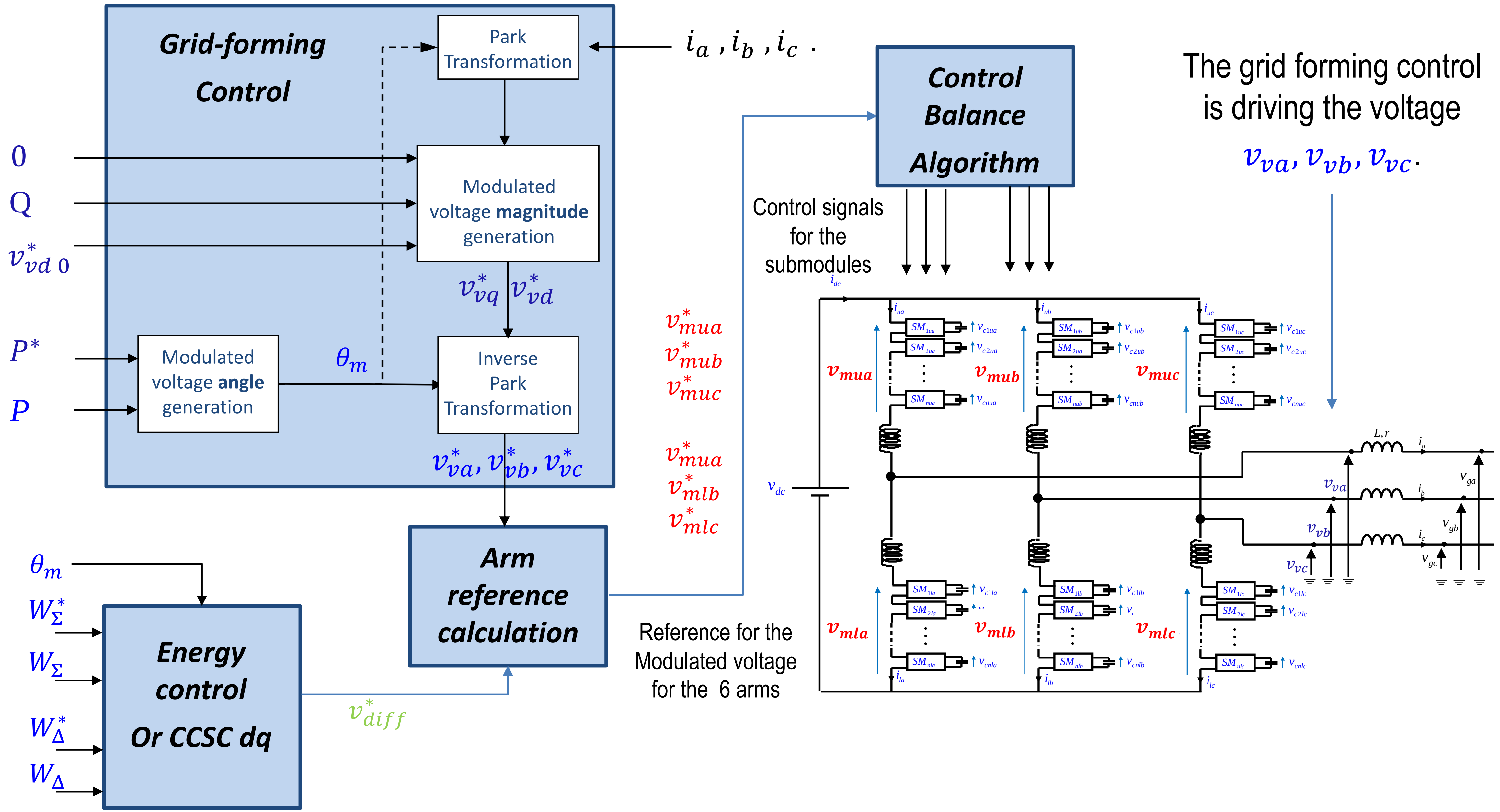
High-Pass filter
to enable damping only
on transients

$0.1 < R_{LCL_D} < 1$

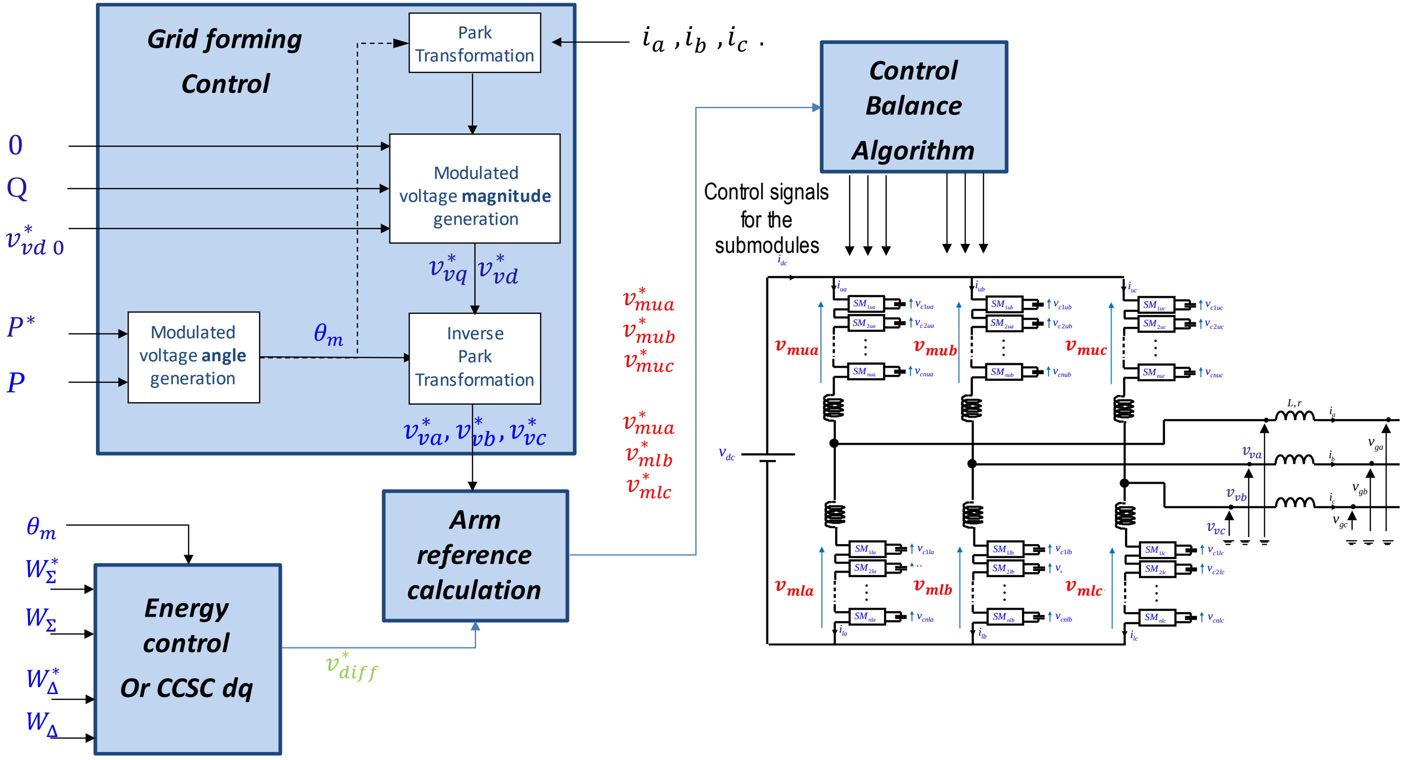
Dynamic decoupling between inner & outer control loops :



Dynamic responses are the same



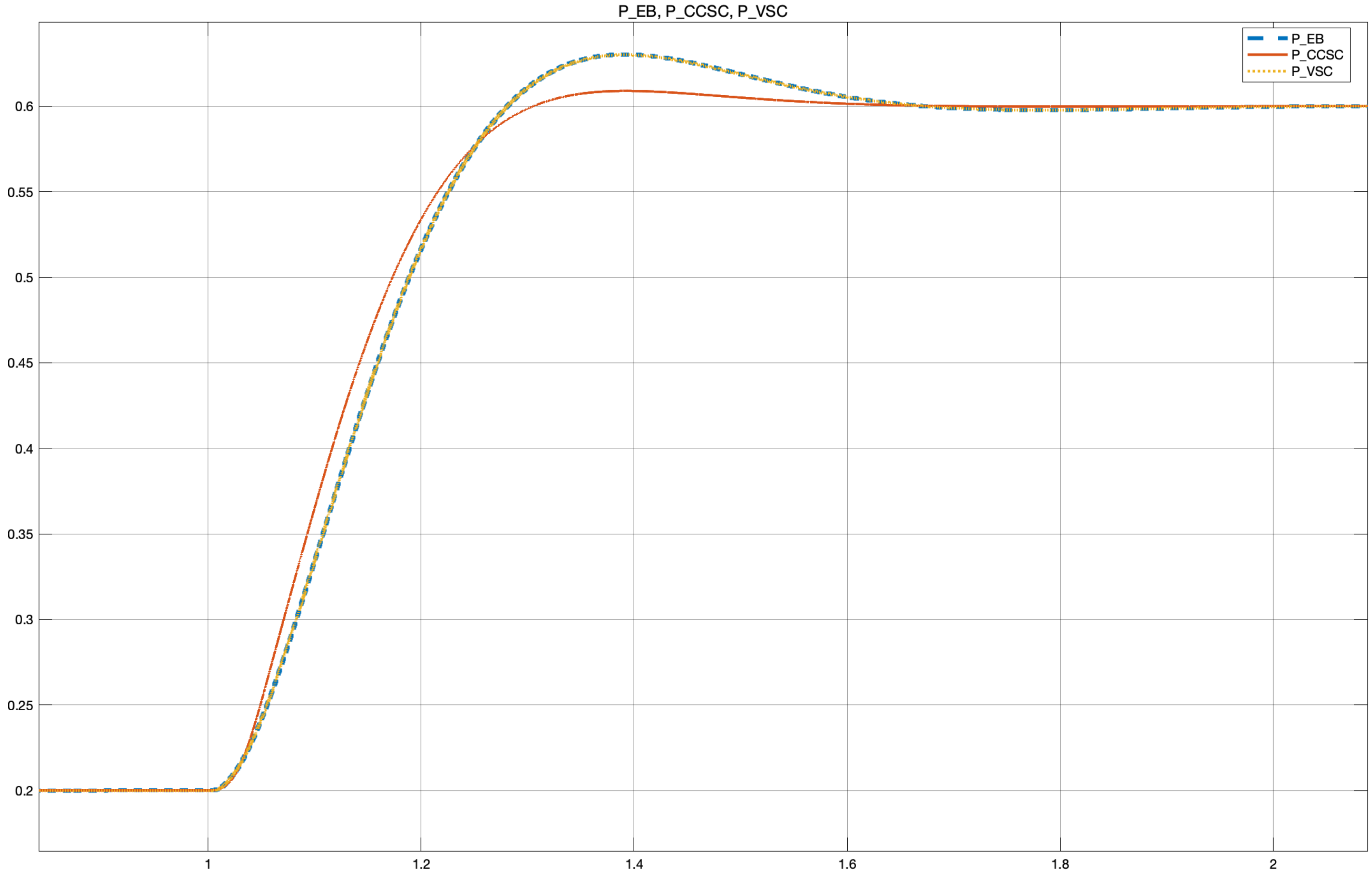
The grid forming control is driving the voltage v_{va}, v_{vb}, v_{vc}.



The energy control or CCSC dq control is unchanged compared with a classical MMC control.
In case of an full energy control, the dynamic behavior is nearly similar to an ideal VSC with an output filter equal to : Lf + Larm/2

Interaction between the power control and energy control

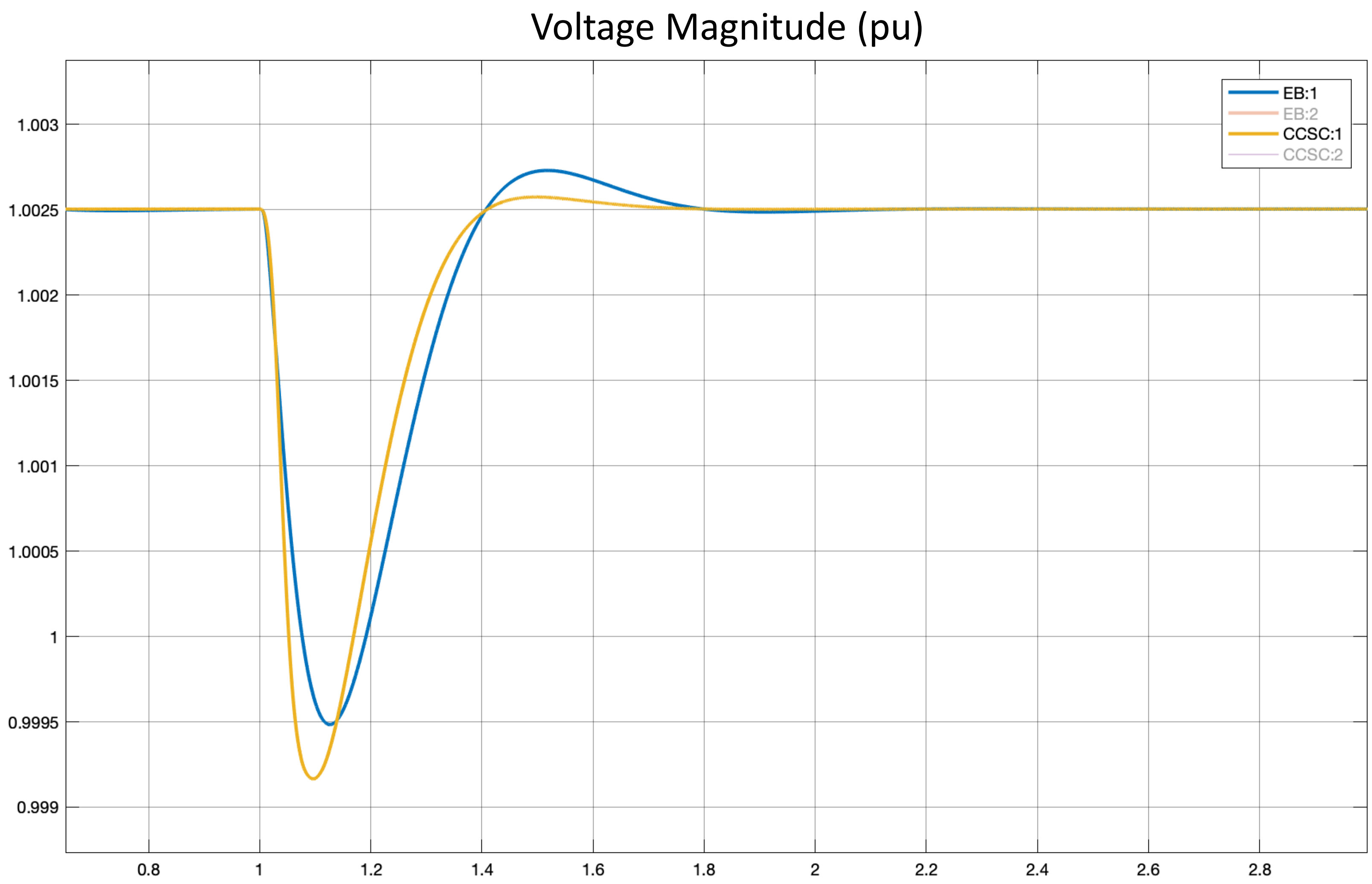
In non-energy-based MMC the energy is stabilized naturally



Interaction between the power control and energy control

In non-energy-based MMC the energy is stabilized naturally

=> AC output voltage is not correctly controlled in non-Energy based



Current limitation in a converter driven by a grid-forming control

The power converter are extremely sensitive to over current, it is compulsory to embed a current limitation functionality in the control of any converter.

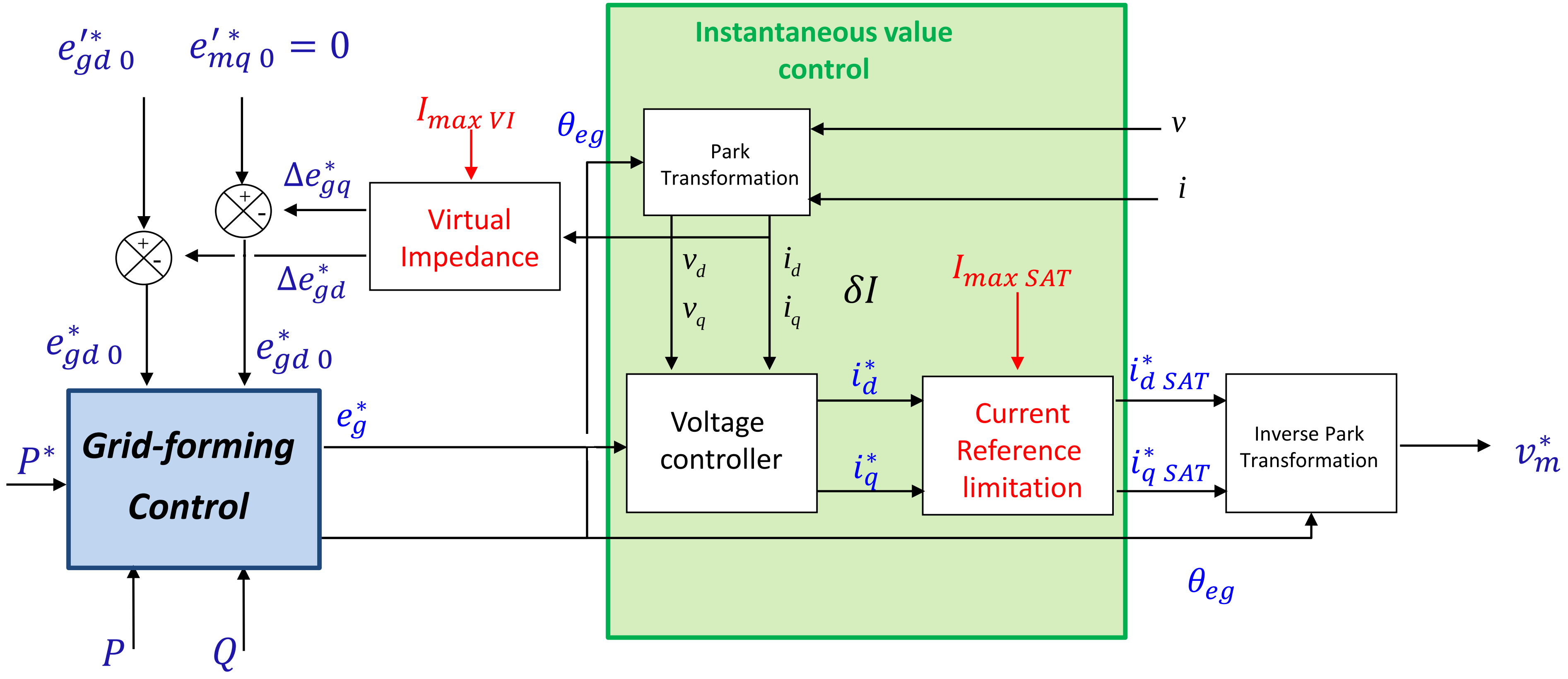
In grid following control, a current loop is implemented then, assuming that the current is correctly controlled by this current loop, a limitation on the current reference implies a limitation on the current itself.

In the different types of control presented previously, no explicit current limitation is embedded. This functionality has to be activated when it is needed.

Two main solutions exist :

Current reference limitation

Virtual Impedance.



A virtual impedance is added in series with the voltage source.

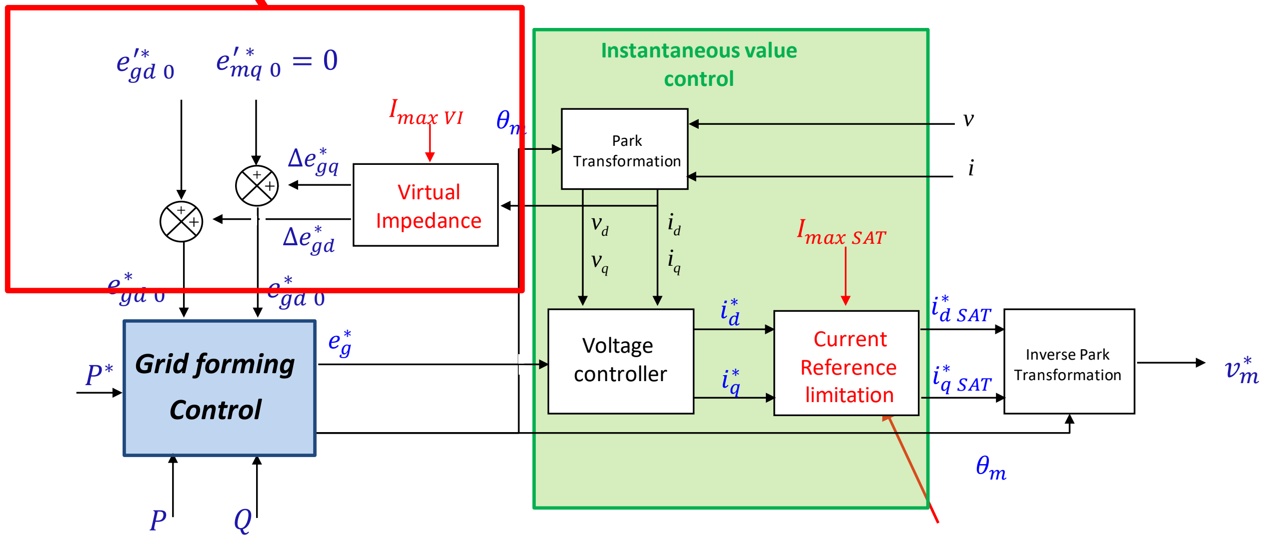
Virtual impedance (VI)

$$e^*_{gd\,0} = e'^*_{gd\,0} - (R_{VI} i_{s_d} - X_{VI} i_{s_q})$$
$$e^*_{gq\,0} = e'^*_{gd\,0} - (R_{VI} i_{s_q} + X_{VI} i_{s_d})$$

where

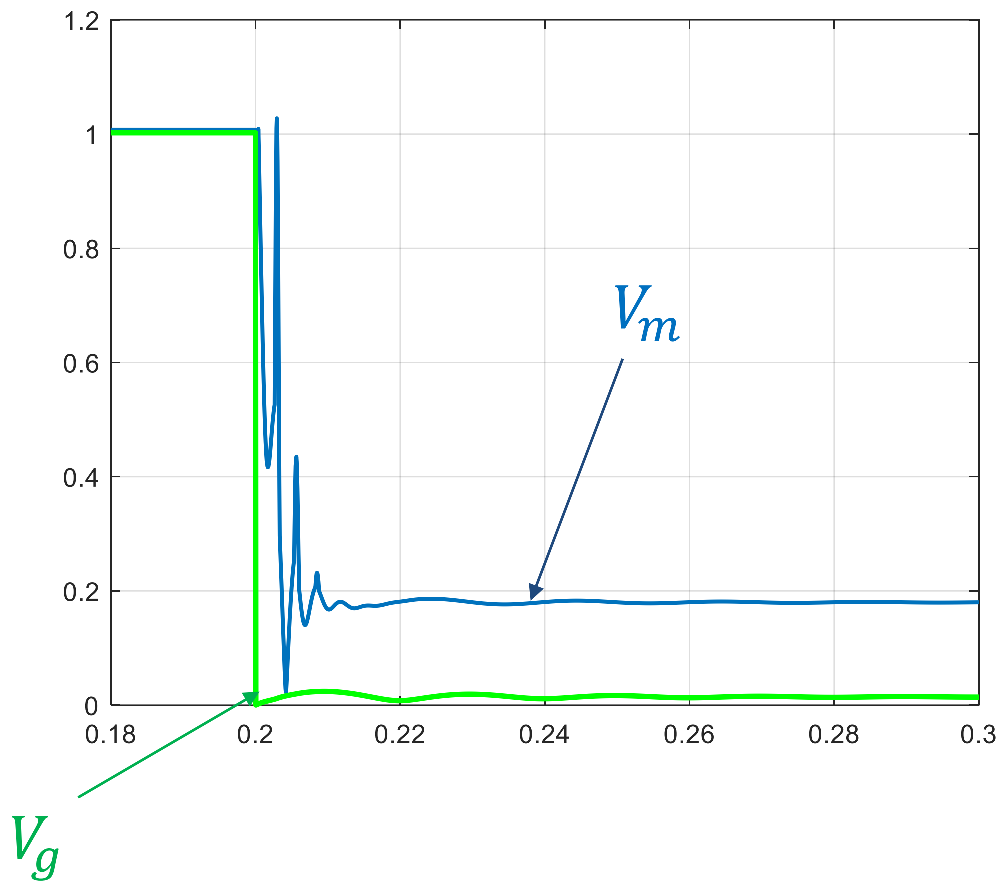
$$X_{VI} = \begin{cases} 0 & if\ \delta I \leq 0 \\ k_{p_{R_{VI}}} \sigma_{X/R} \delta I & if\ 0 < \delta I \leq \delta I_{max} \\ k_{p_{R_{VI}}} \sigma_{X/R} \delta I_{max} & if\ \delta I > \delta I_{max} \end{cases}$$

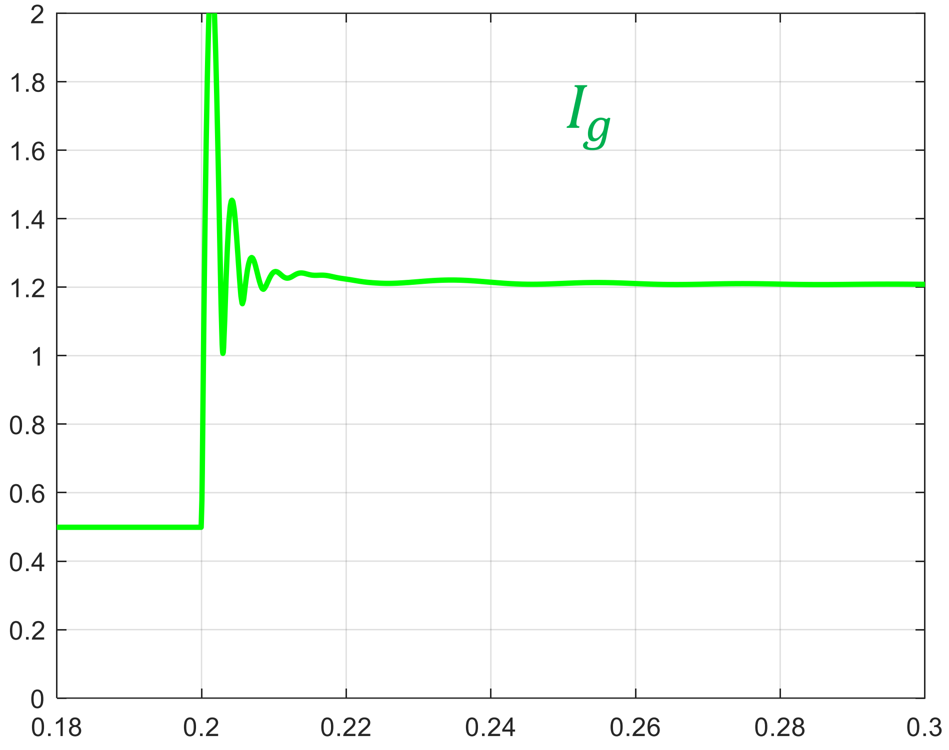
$$\delta I_{pu} = I - 1$$
$$\delta I_{\max\ pu} = I_{\max VI} - 1$$
$$R_{VI} = X_{VI}/\sigma_{X/R}$$



Indirect action on the output current

Current limitation in case of a voltage sag with a virtual impedance



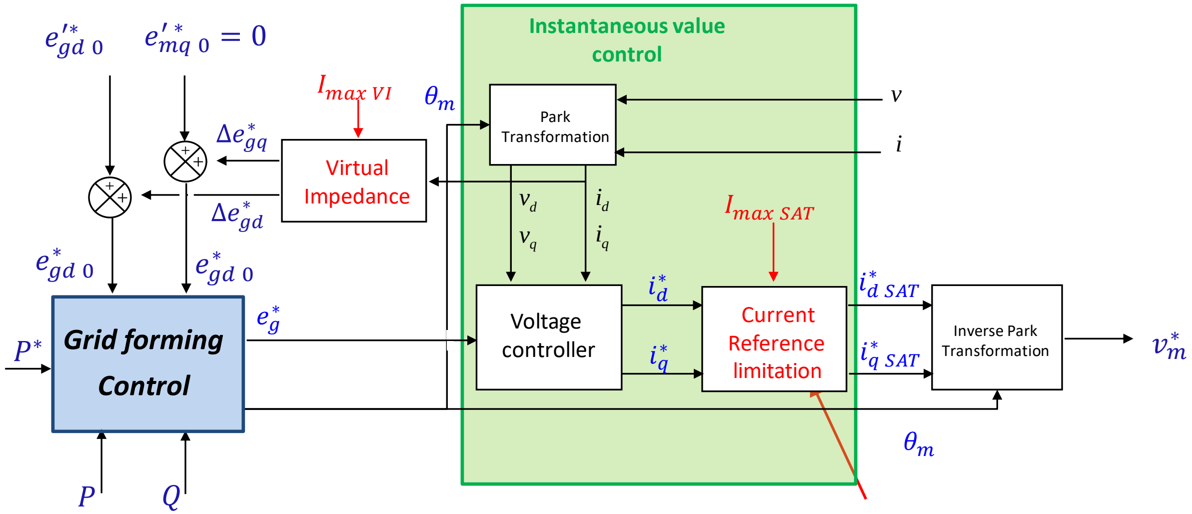


Large overshoot on I_g during the transient

Current Limitation

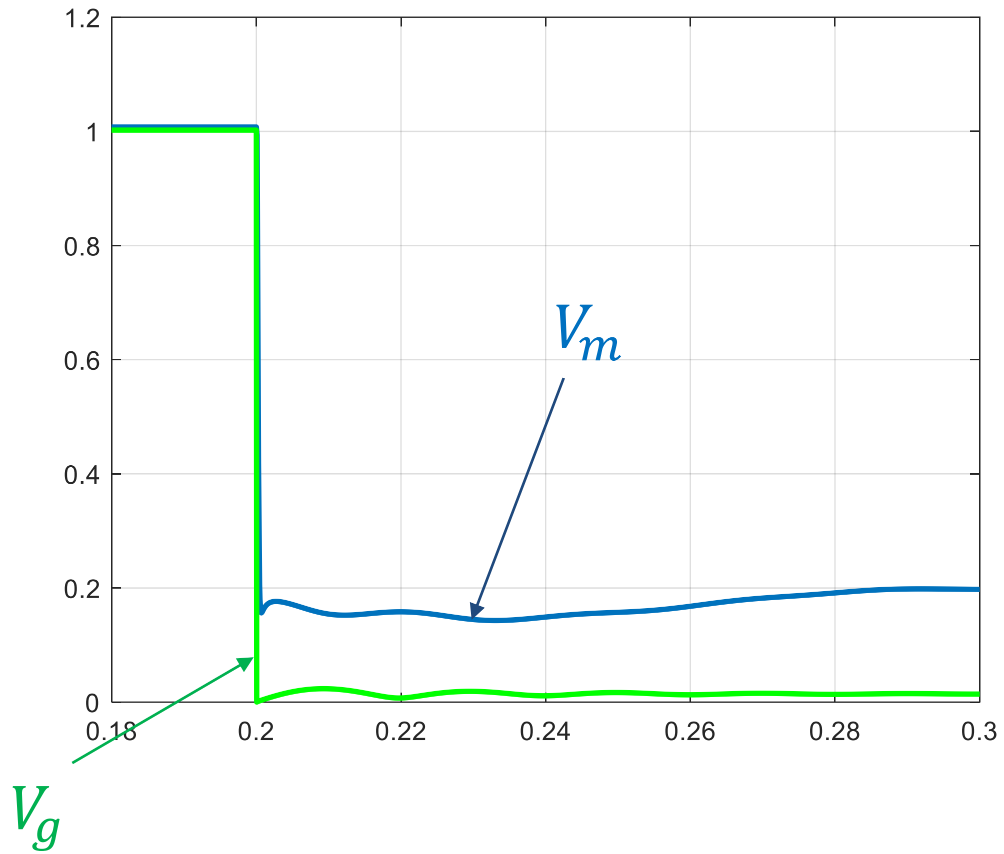
$$\begin{cases} |i^*_{s_{ds}}| = \min(I_{max_{SAT}}, |i^*_{s_d}|) \\ |i^*_{s_{qs}}| = \min(\sqrt{I^2_{max_{SAT}} - {i^*_{s_{ds}}}^2}, |i^*_{s_q}|) \end{cases}$$

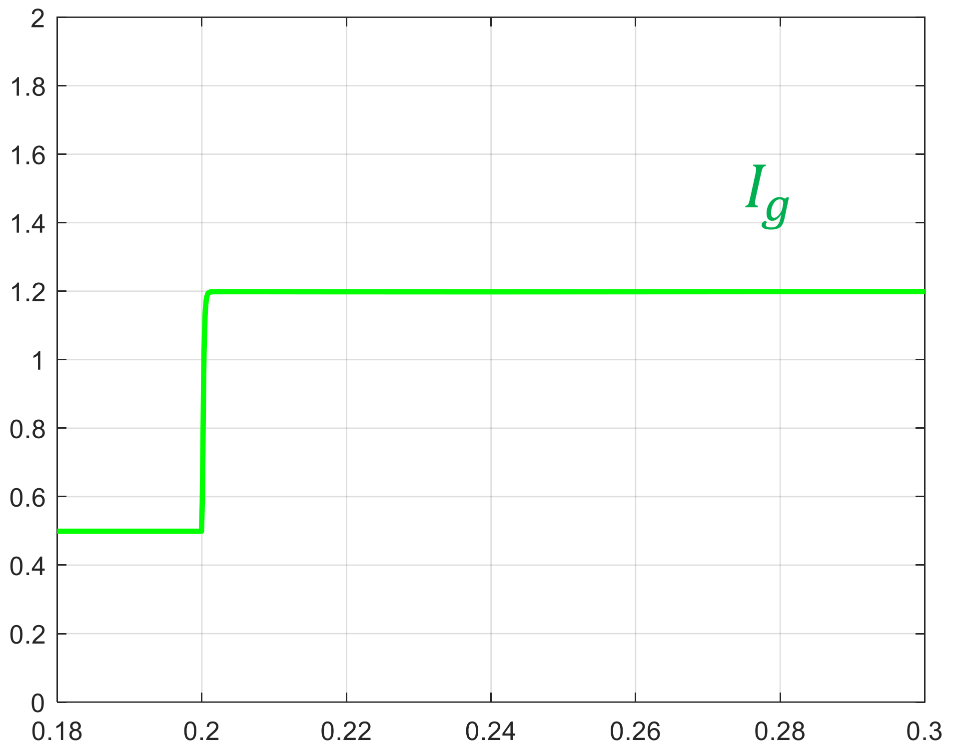
Direct action on the output current



When combining both current limitations algorithms, it is possible to take advantage of the advantages of both of them

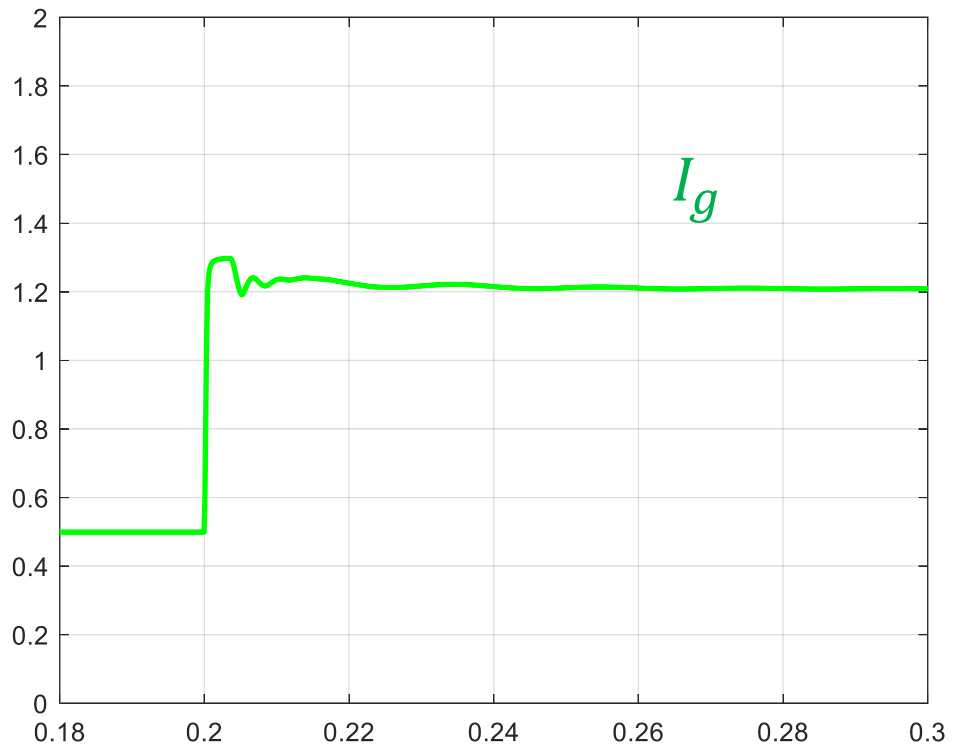
Current limitation in case of a voltage sag with a current loop





Combinaison of

Current limitation (Sat : 1.3) + virtual impedance (Sat 1.2)

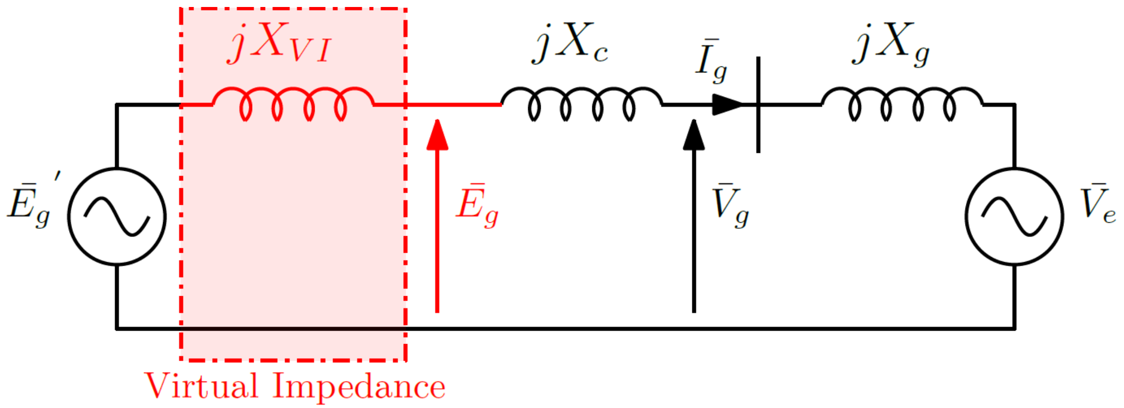


The current saturation seems to be better than the virtual impedance.

However the resynchonization has to be studied.

The steady state model is still very usefull to analyse what happens in case of a short circuit.

In steady state the system may be represented by the following electrical circuit



With

- X_{VI} : virtual impedance
- X_c : connection impedance
- X_g : grid impedance

$$\bar{E}_g = E_g e^{j\delta_{eg}} \qquad \bar{V}_e = V_e e^{j\delta_e}$$

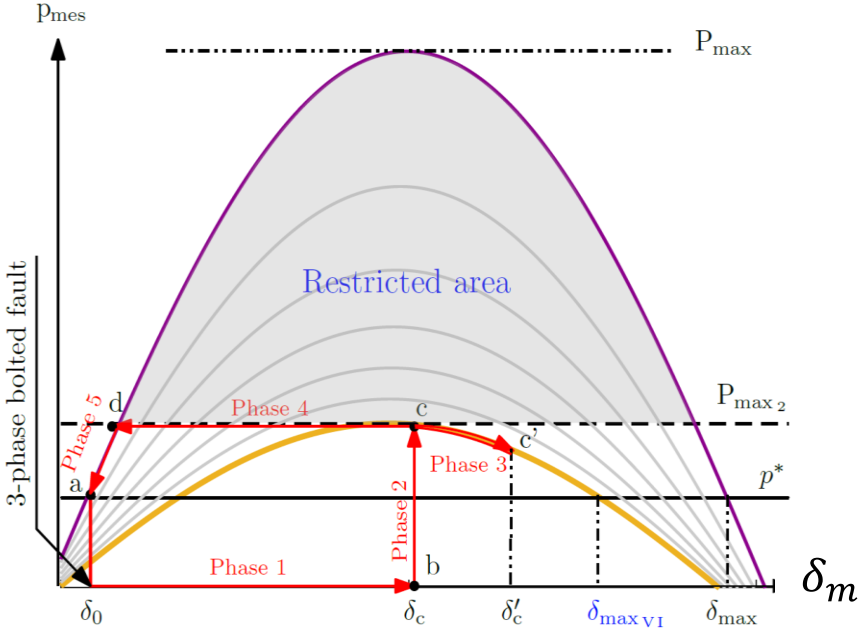
$\bar{V}_e$ is choosen as phase reference δ_e =0

$$P = \frac{E_g' V_e}{X_c + X_g + X_{VI}} \sin \delta_{eg}$$

Using the steady state model, it is possible to draw an infinite number of curves depending on the virtual impedance

These curves are very helpfull to understand what happens in case of a bolted fault

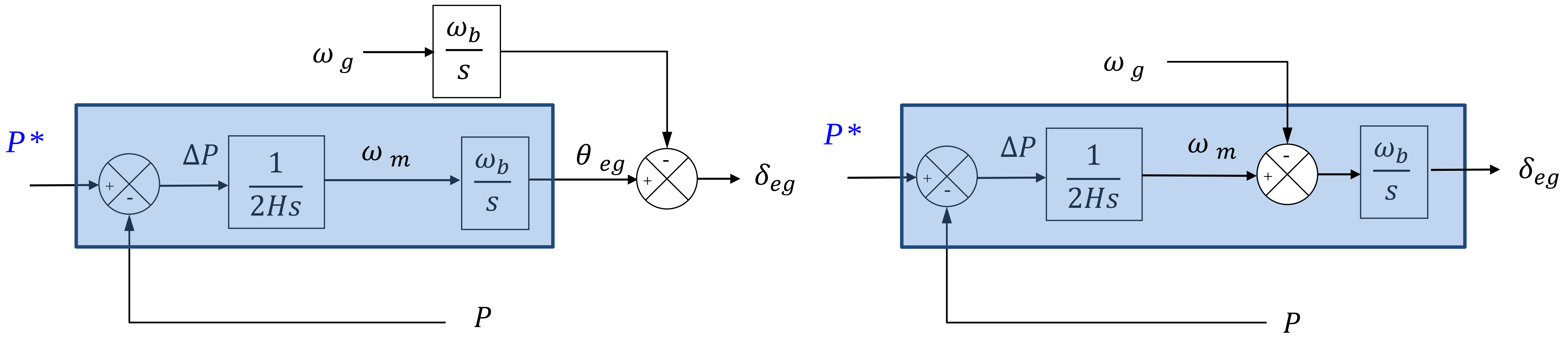
$$P = \frac{E'_g V_e}{X_c + X_g + \cancel{X_{VI}}} \sin \delta_{eg}$$



$$P_{max} = \frac{E'_g V_e}{X_c + X_g + X_{VI_{max}}}$$

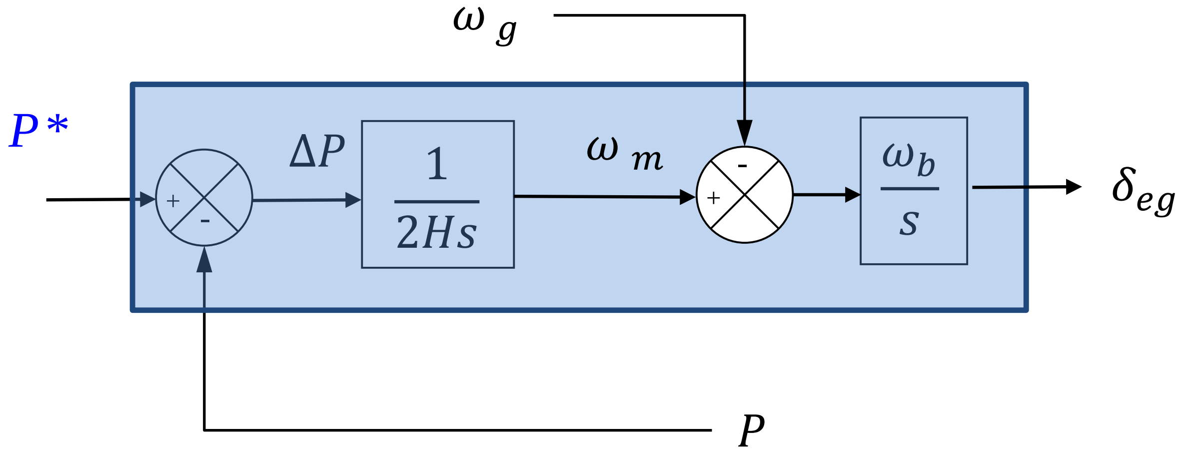
Link between the phasor and EMT angle

δ_{eg} is the phasor angle associated to $\theta_{eg} = \omega_g t + \delta_{eg}$ With ω_g: grid frequency

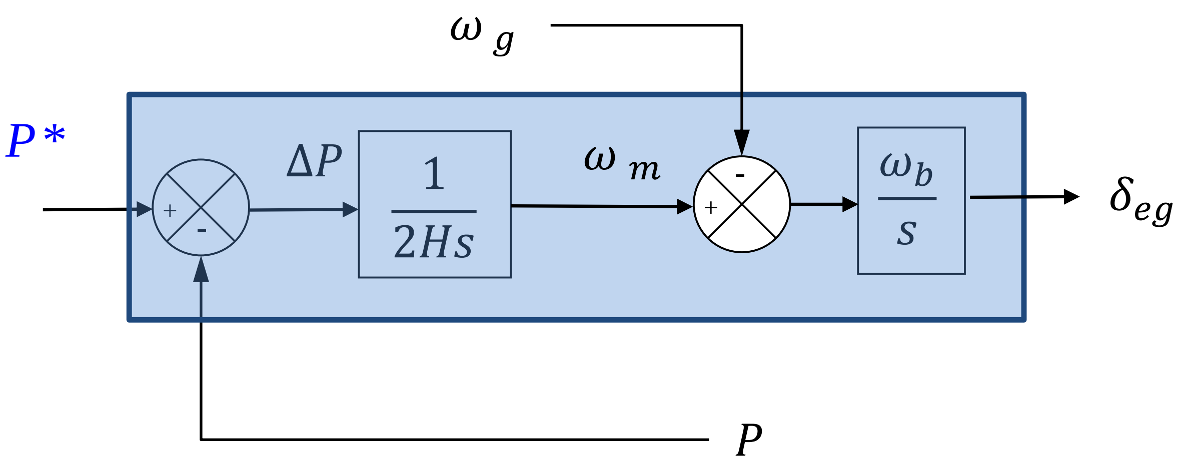


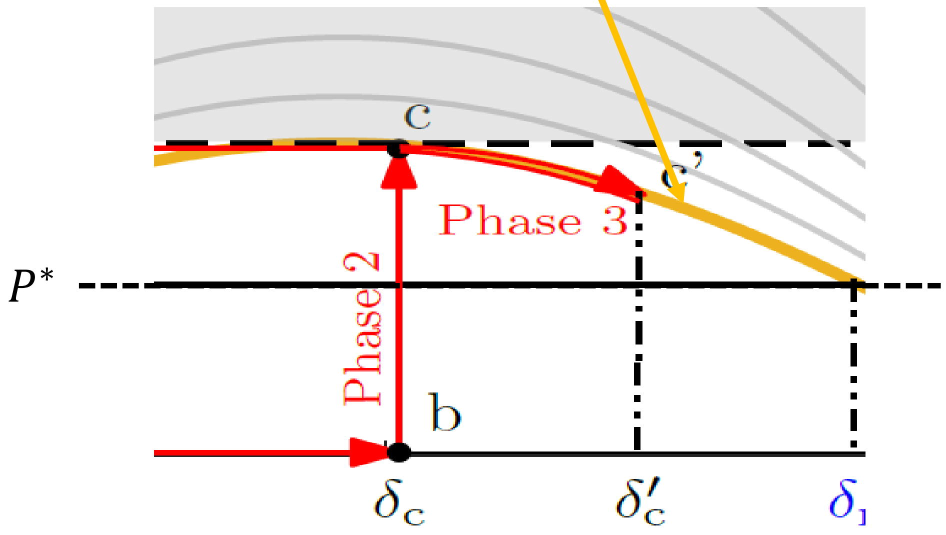
During a bolted fault, $P = 0$

$\Delta P > 0$ ⇒ ω_m increases and becomes superior to ω_g ⇒ δ_{eg} increases



When the voltage recovers, (phase 2) the active power reaches the yellow curves

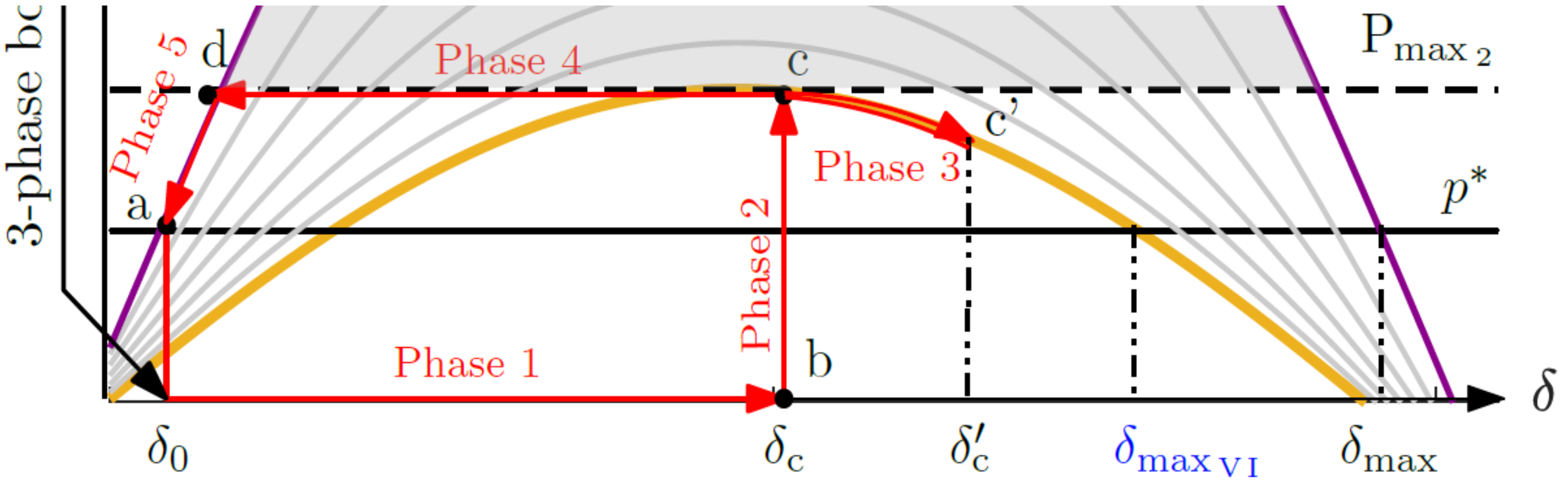




$\Delta P < 0$ Which means that ω_m starts decreasing

But δ_{eg} still increases : (phase 3)

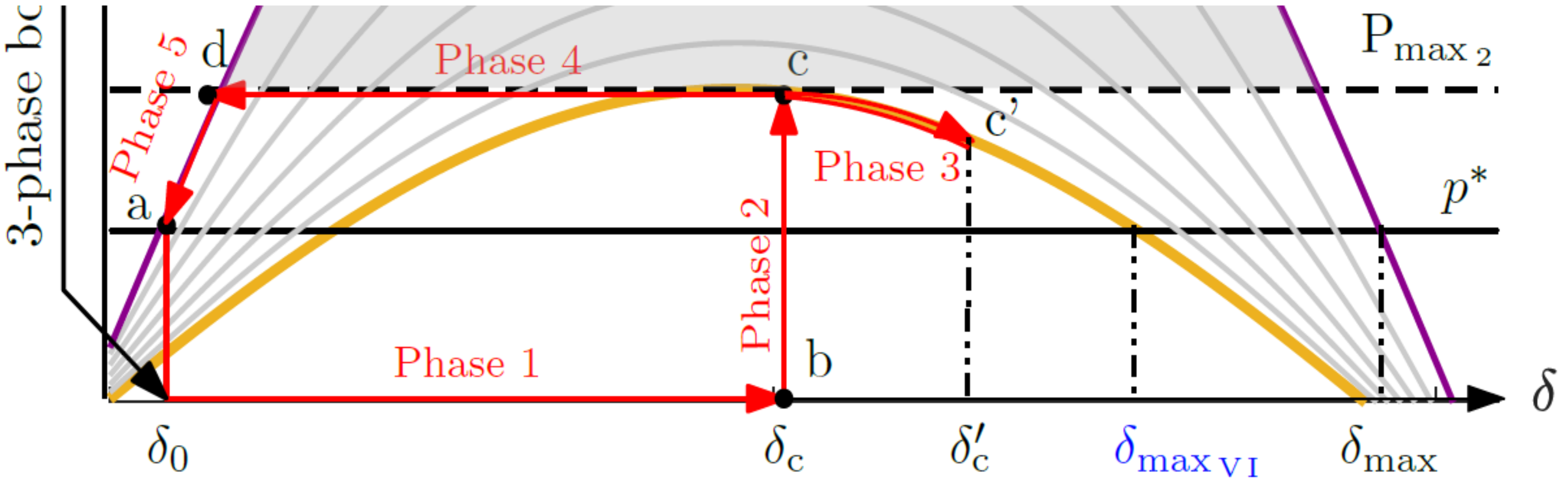
$$P = \frac{E'_g V_e}{X_c + X_g + X_{VI_{max}}} \sin \delta_{eg}$$



When ω_m becomes inferior to ω_g then δ_{eg} decreases (phase 4)

During (phase 4), the virtual impedance start to decrease to 0

When reaching the curve $P = \frac{E_g' V_e}{X_c + X_g} \sin \delta_{eg}$ then the virtual impedance becomes null.



In (phase 5) the virtual impedance is cancelled but the active power is still different from P^*

The full sequence is finished when the operating point recovers its initial value P^*:

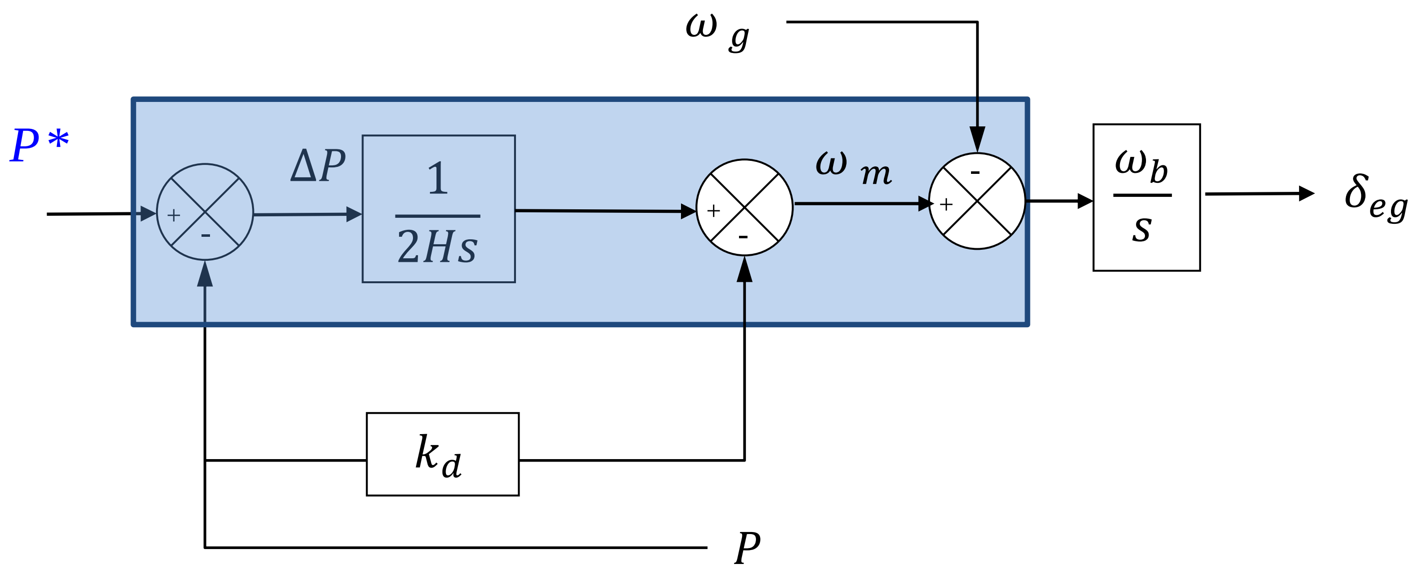
The grid forming control is able to resynchronize with no external information.

This phenomena is similar to a synchronous machine and the transient stability could be explained thanks to the classical tool : **the equal area criterion**

But

Unlike for the synchronous machine, H can be modified by the control.

A damping effect (kp) can be tuned



It is possible to limit the variation on δ_{eg} to avoid transient instability **by increasing H or decreasing P^***

The question is : how is it possible to manage these values with no external signal which inform about the fault ?

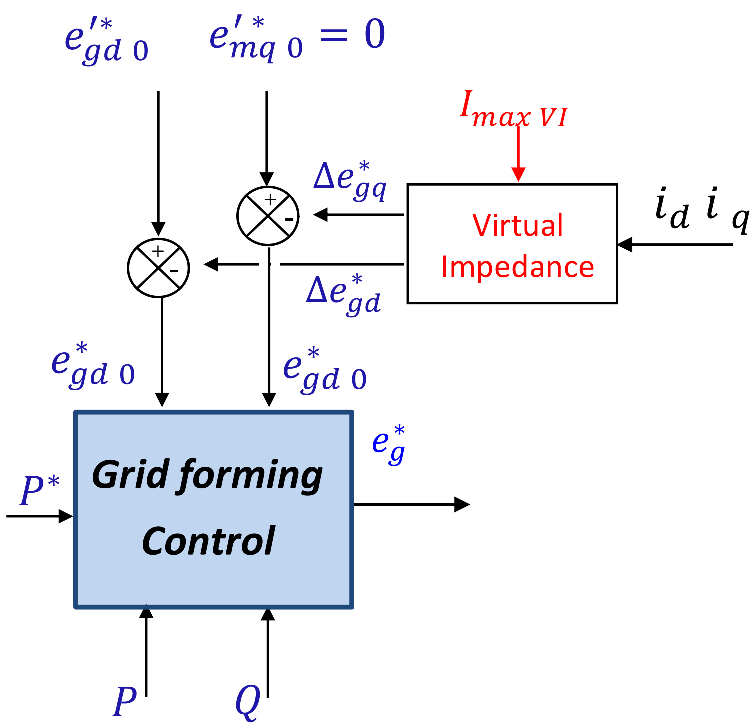
It has been found that the magnitude of e_g^* was a good indicator to modify the inertia

$$H = \frac{H_0}{\sqrt{\left(e'^{*}_{g_{d0}} - \Delta e^{*}_{g_d}\right)^2 + \left(e'^{*}_{g_{q0}} - \Delta e^{*}_{g_q}\right)^2}}$$

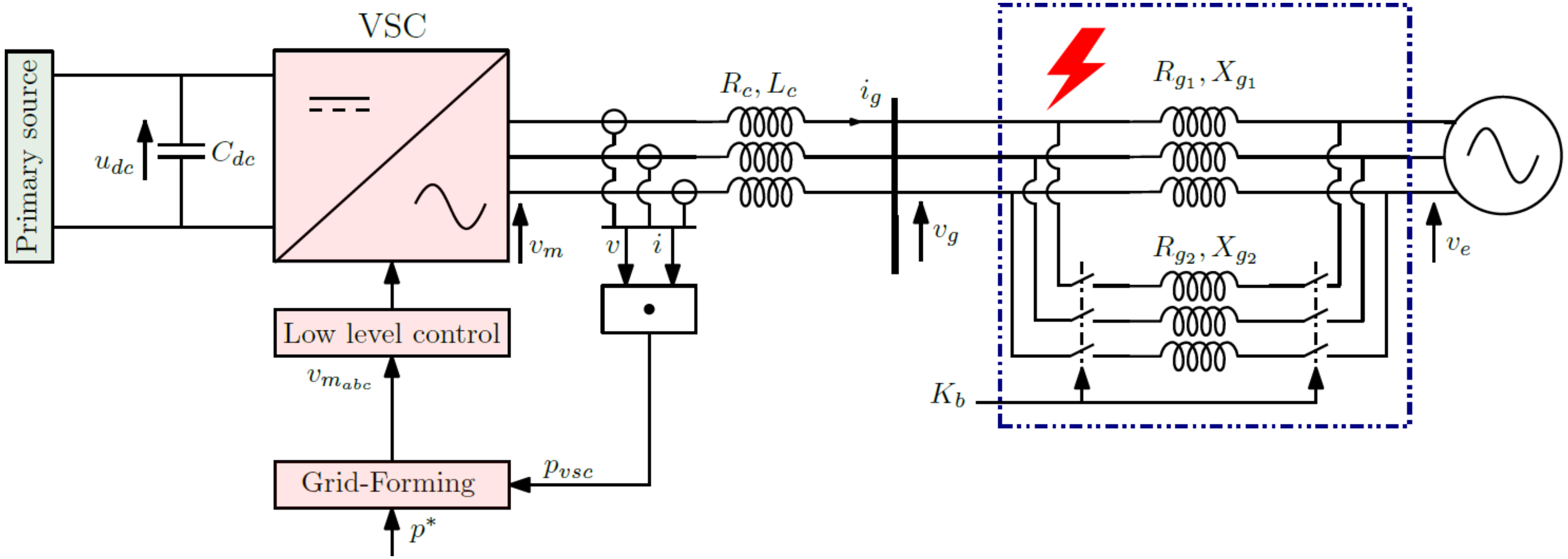
H_0 is the inertial in normal operation

In case $e'^{*}_{g_{d0}}$=1 and $e'^{*}_{g_{q0}}$=0

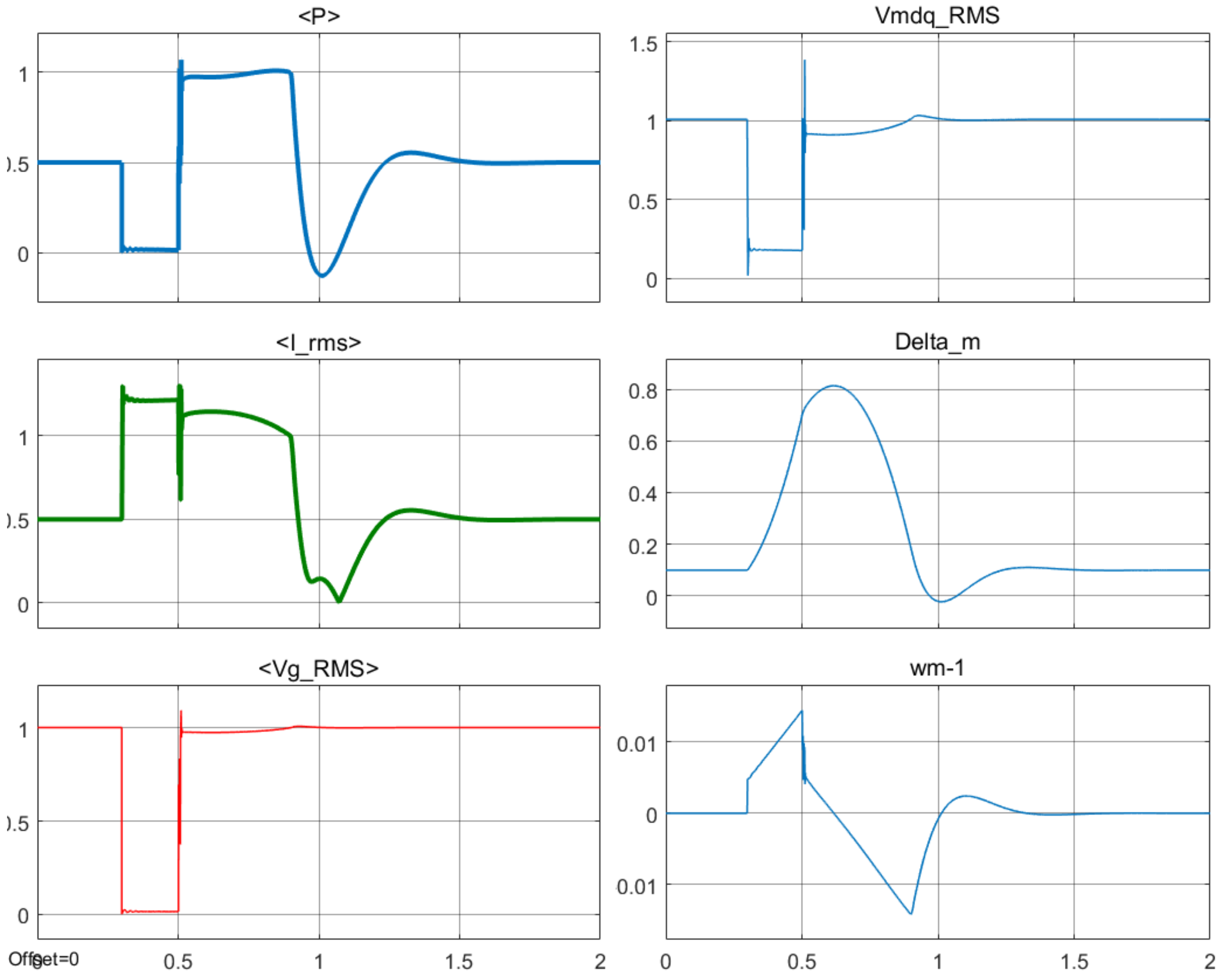
$$H = \frac{H_0}{\sqrt{\left(1 - \delta e^{*}_{g_d}\right)^2 + \delta e^{2^*}_{g_q}}}$$



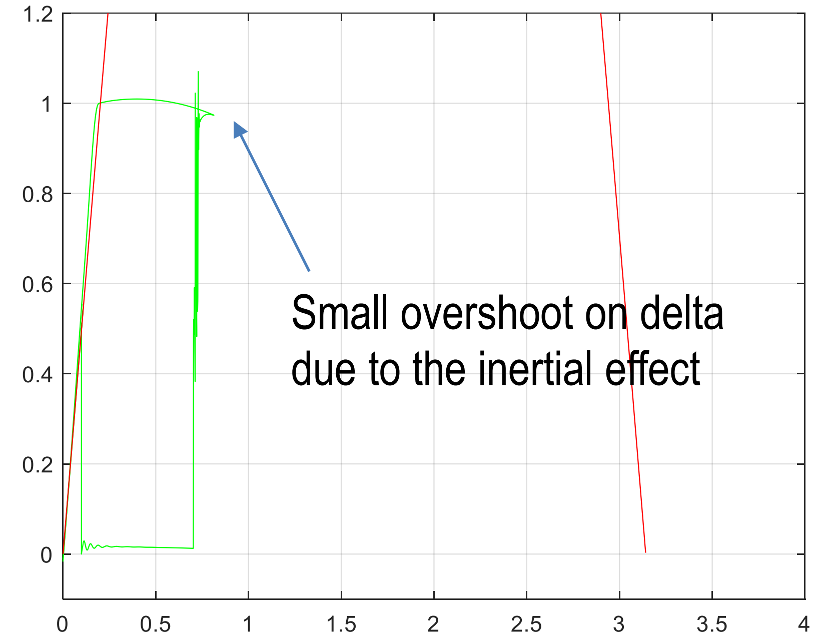
A 200 ms bolted short circuit is applied at the Point Of Common Coupling of the converter



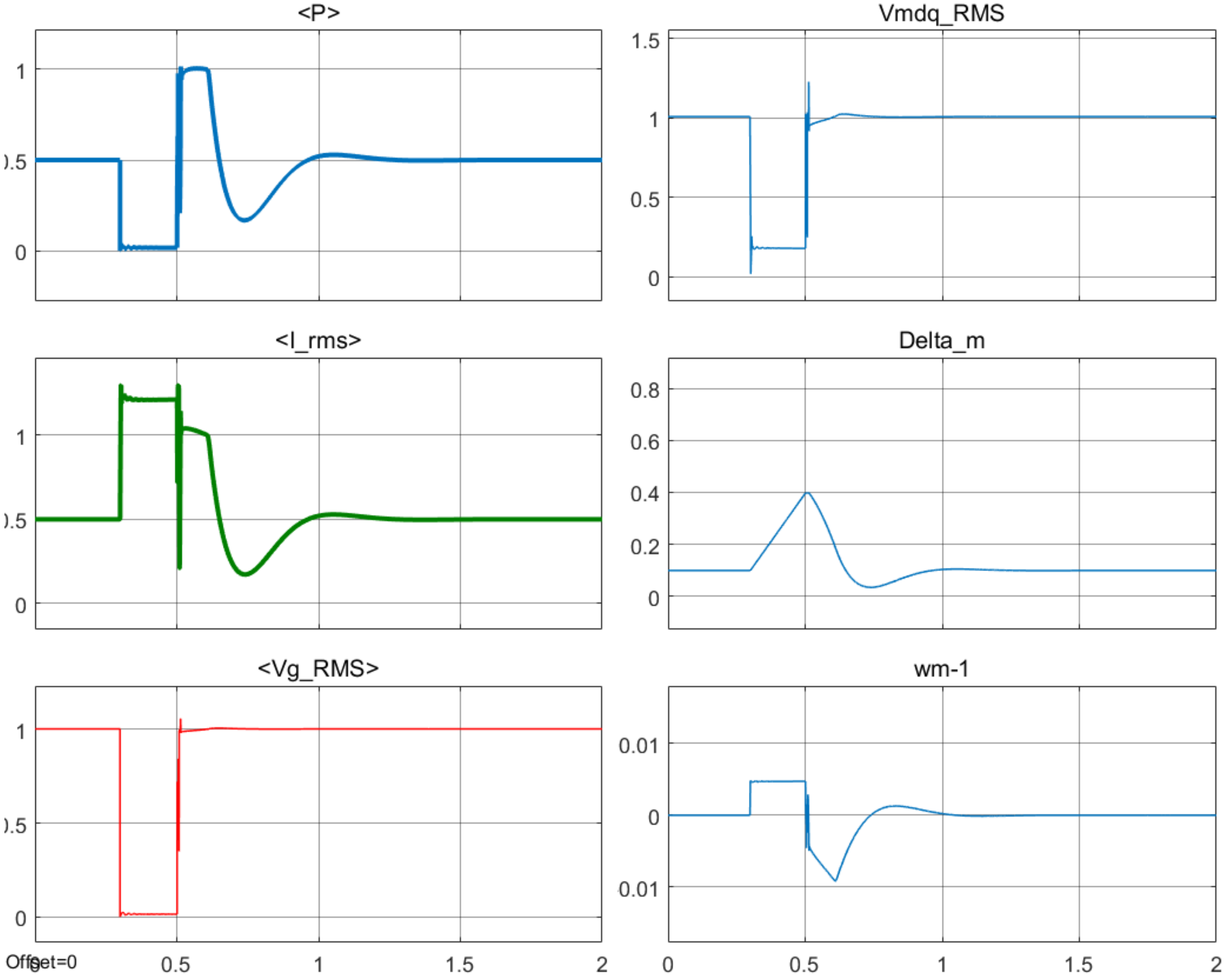
Simulation results for H constant



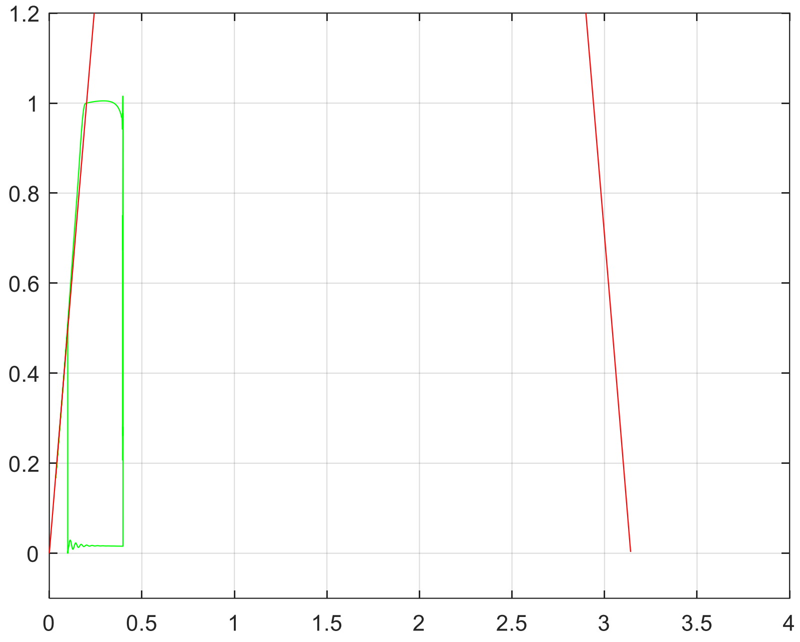
$P(\delta)$ *curve*



Simulation results for H variable

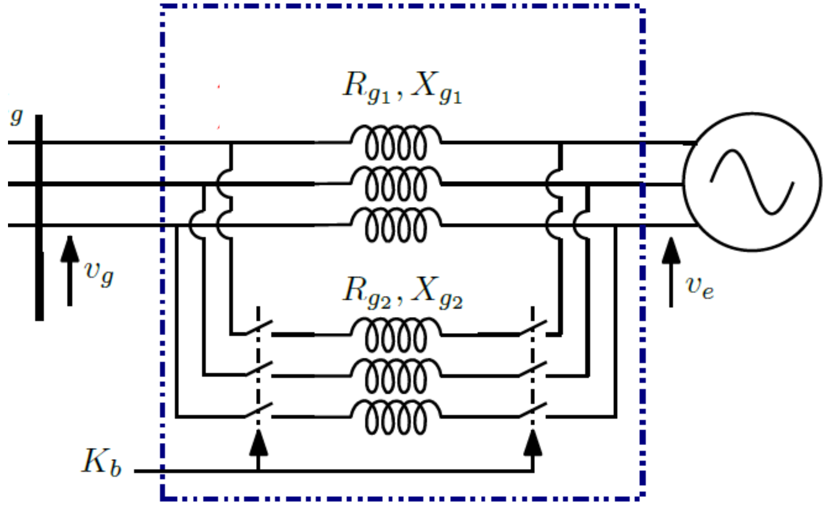


$P(\delta)$ *curve*

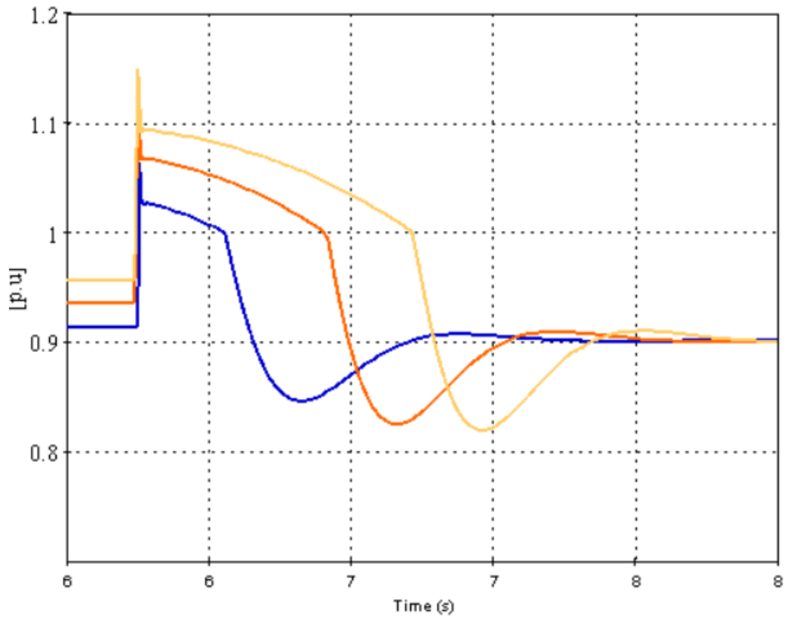


The critical clearing time can be enhanced

The line reclosing can also induce an overcurrent

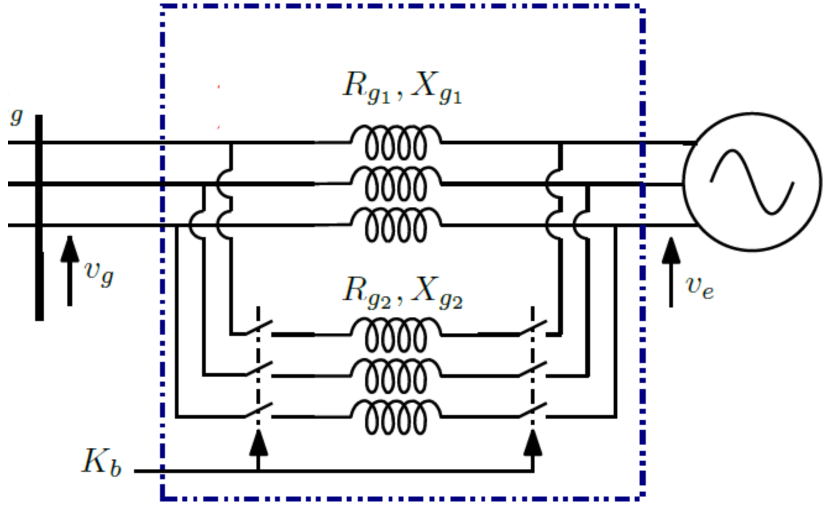


K_b is closed

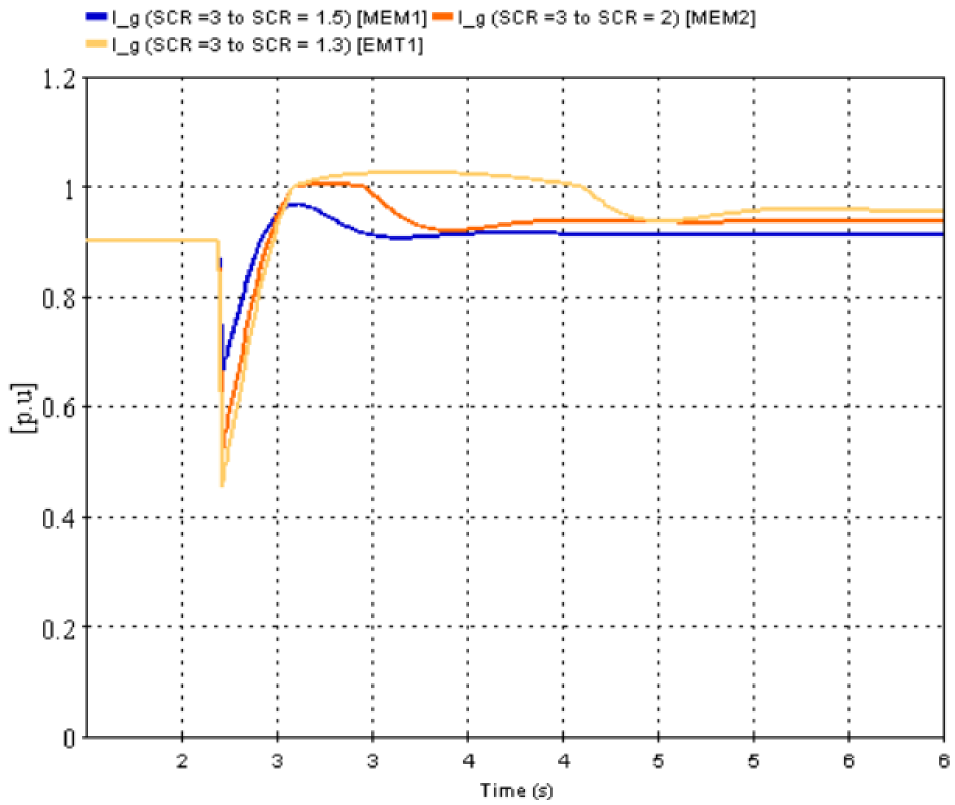


Current in the converter for
various values of SCR variations

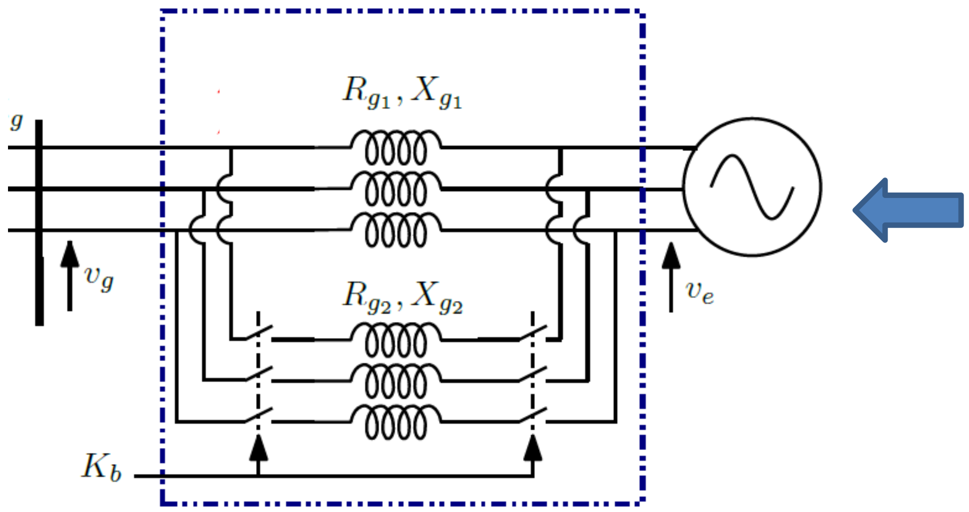
In case, the current reaches its limitation, the virtual impedance algorithm limits the current and the system resynchronizes itself with no external action



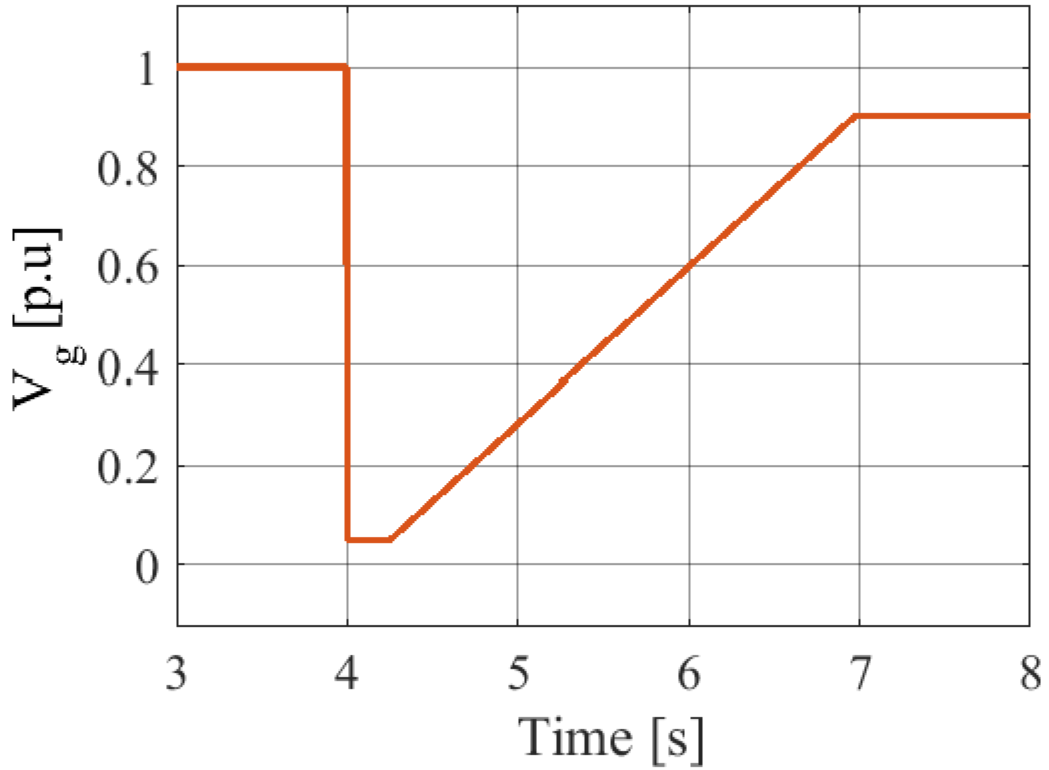
K_b is opened



In some cases, the current reaches its limitation.
Thanks to the virtual impedance algorithm, the system resynchronizes itself after the event with no external action



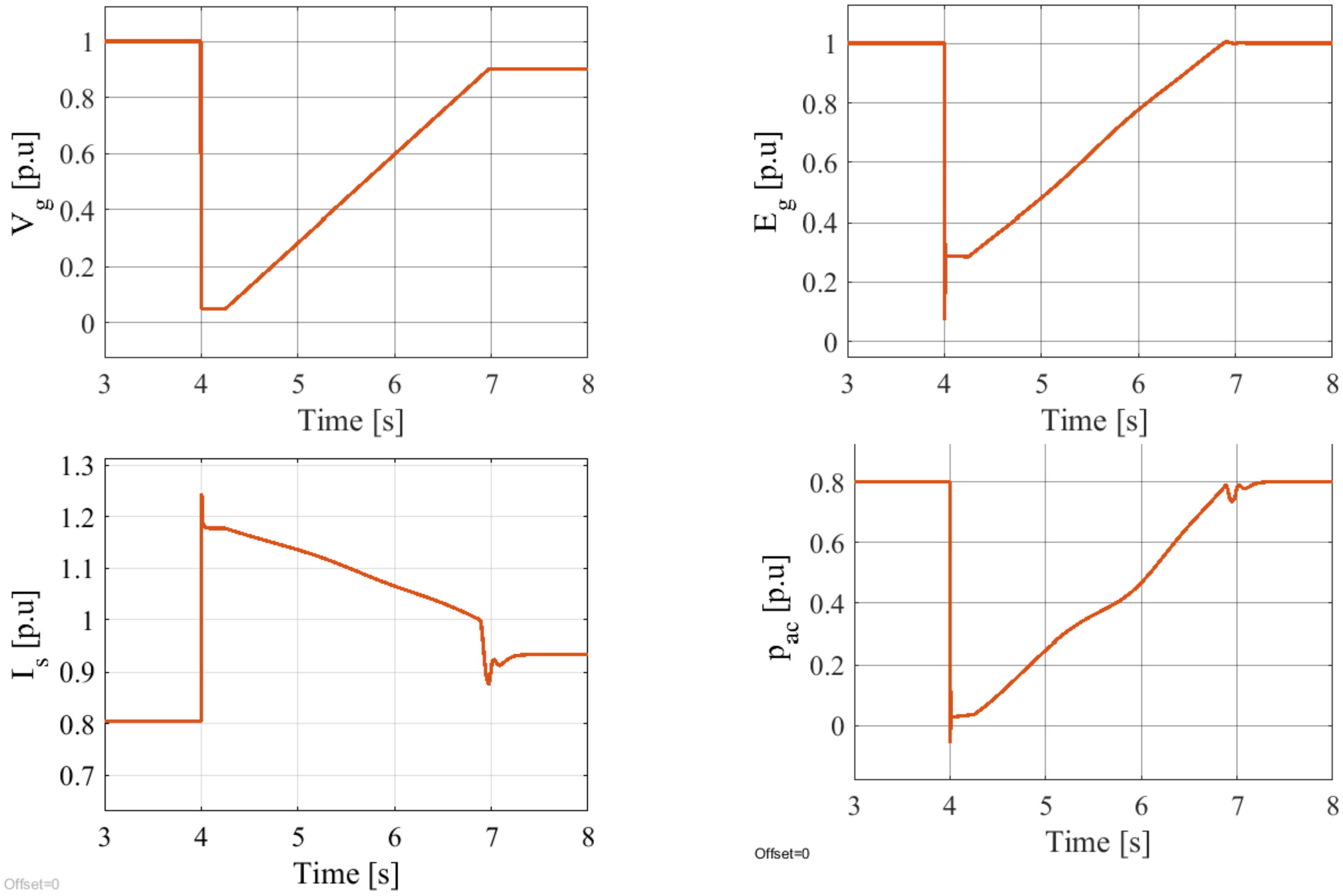
K_b is opened



Requirement for Generator (Rfg) grid code ENTSOE

The worst case has been choosen
250 ms of voltage drop (0.05 pu)
The voltage recovers in 3 s

Voltage ride through test



For this test, it is needed to have a critical clearing time of 3s, at least.

In the previous slides, some considerations have been proposed about transient stability analysis but it is still an on going work

Some pending questions :

What is the best solutions in term of transient stability : virtual impedance or current limitation ?

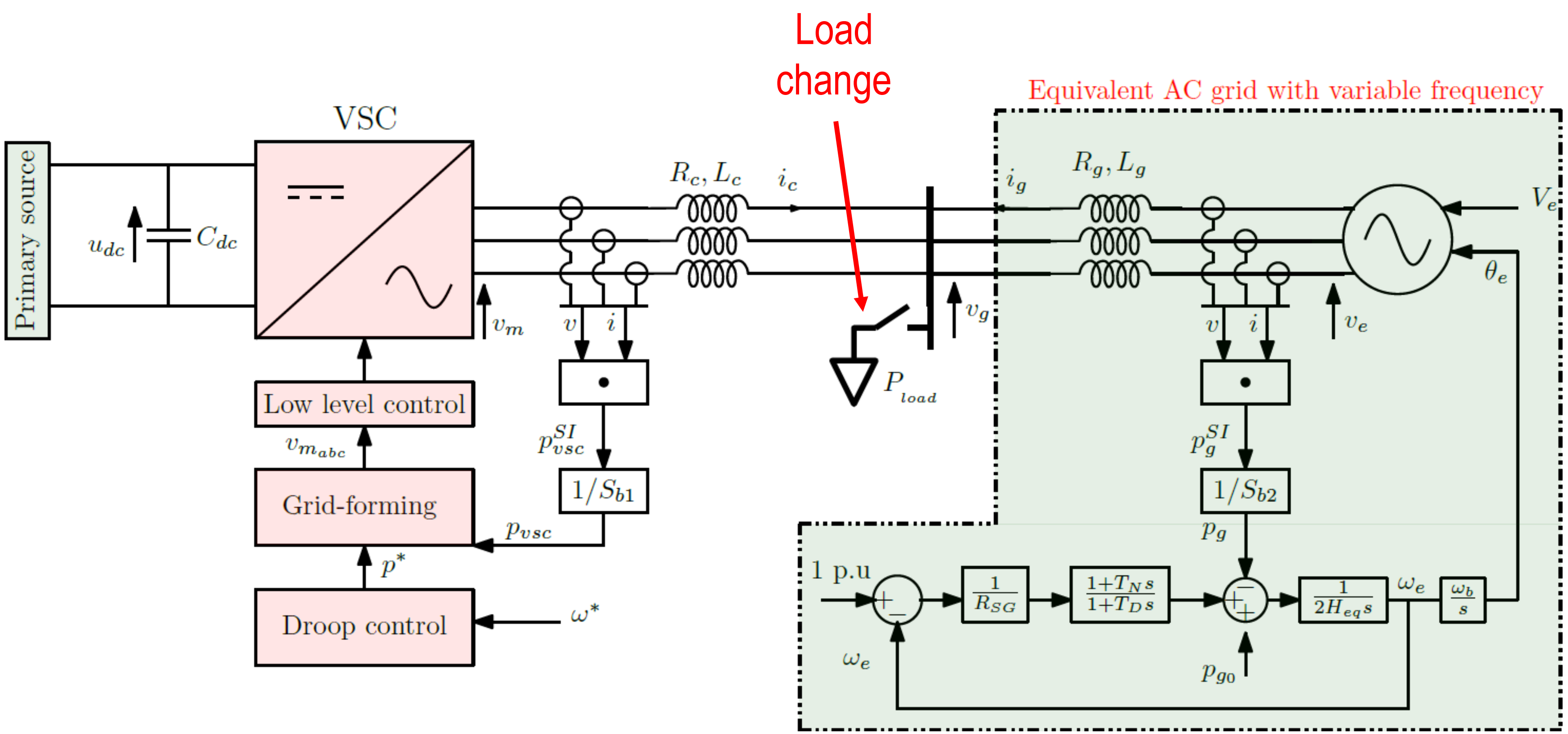
How to calculate the critical clearing time for the different types of control ?

What are the different degrees of freedom available in the control ?

…

Frequency variation on the grid

In order to test the inertial effect a **variable frequency grid** can be implemented

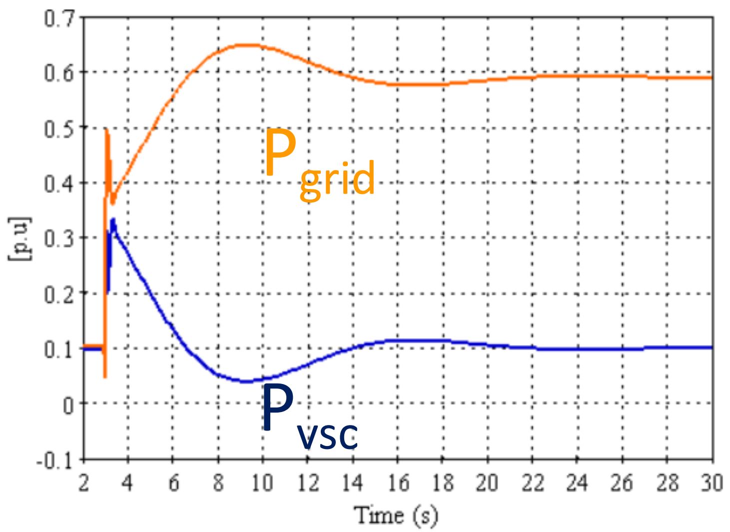


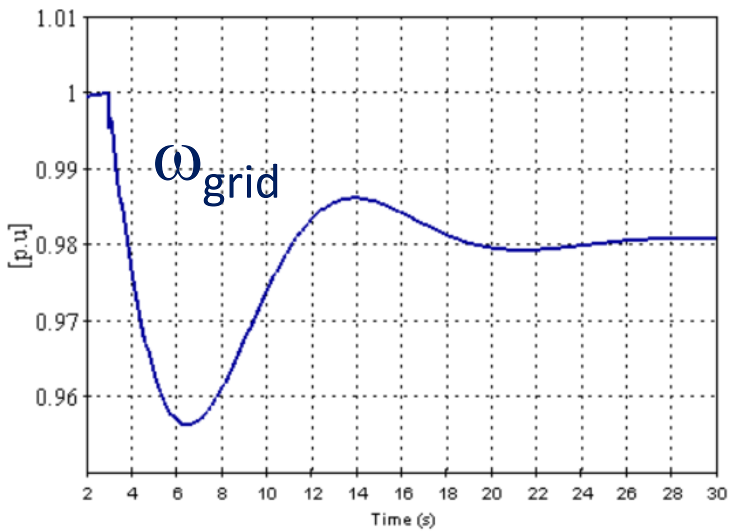
The dynamic behavior of the voltage source can be adjusted with H_{eq}, T_N T_d

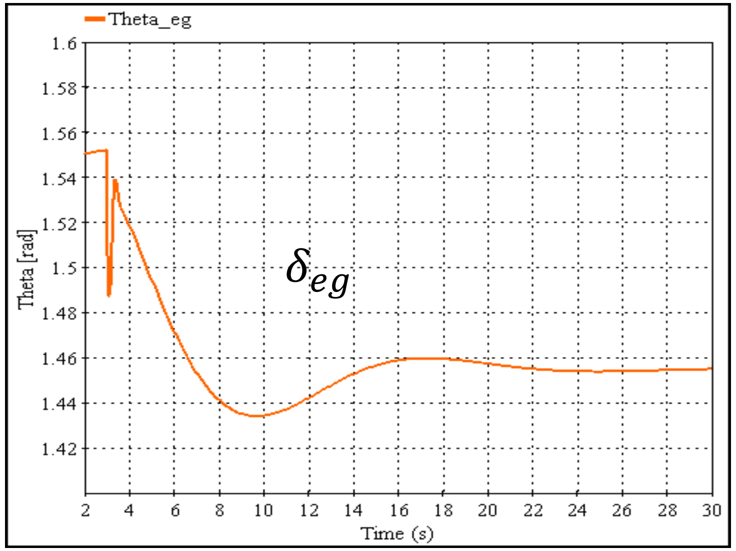
A frequency droop control is embedded to stabilize the frequency in normal range of operation whatever the control on the converter is

$P_{load} = 500$ MW connection at t = 1s.

An inertial effect is included in the grid forming control but no frequency droop

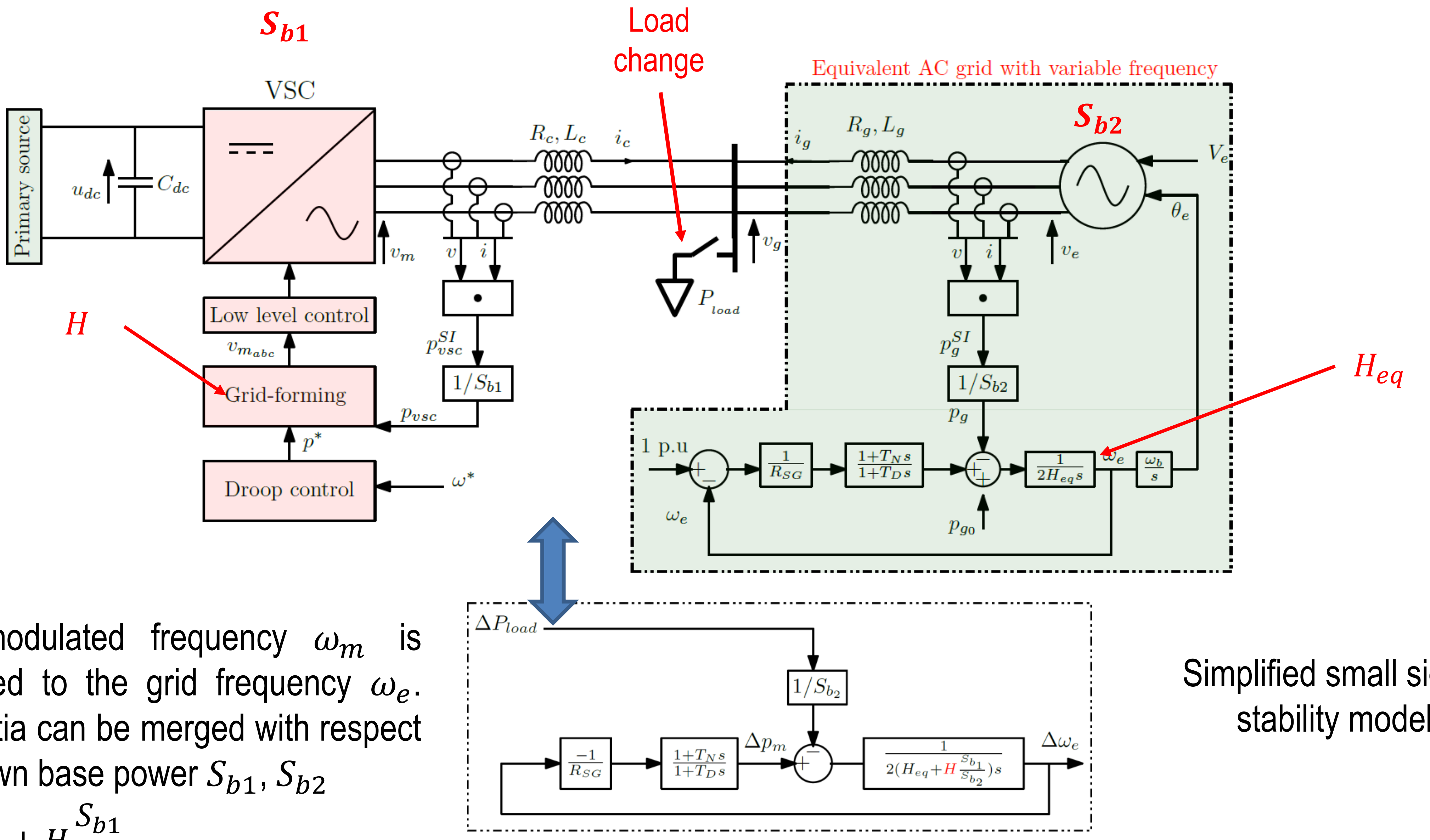






As soon as the frequency decreases, the power increases in the VSC. This is the inertial effect

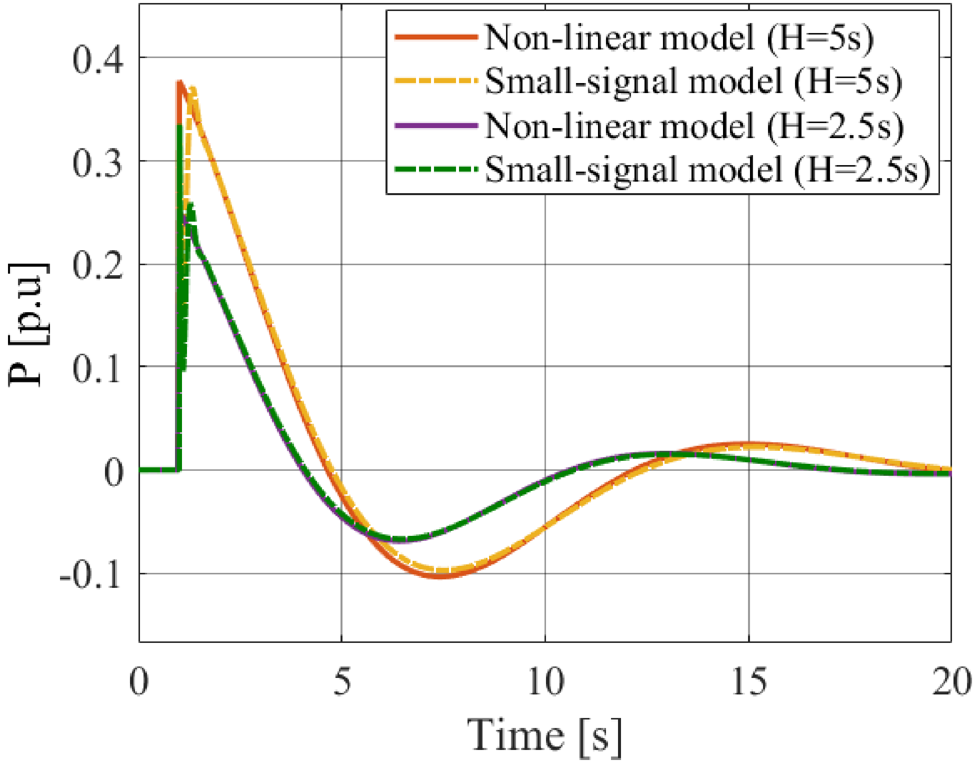
When the frequency recovers, the power comes back to its initial value.

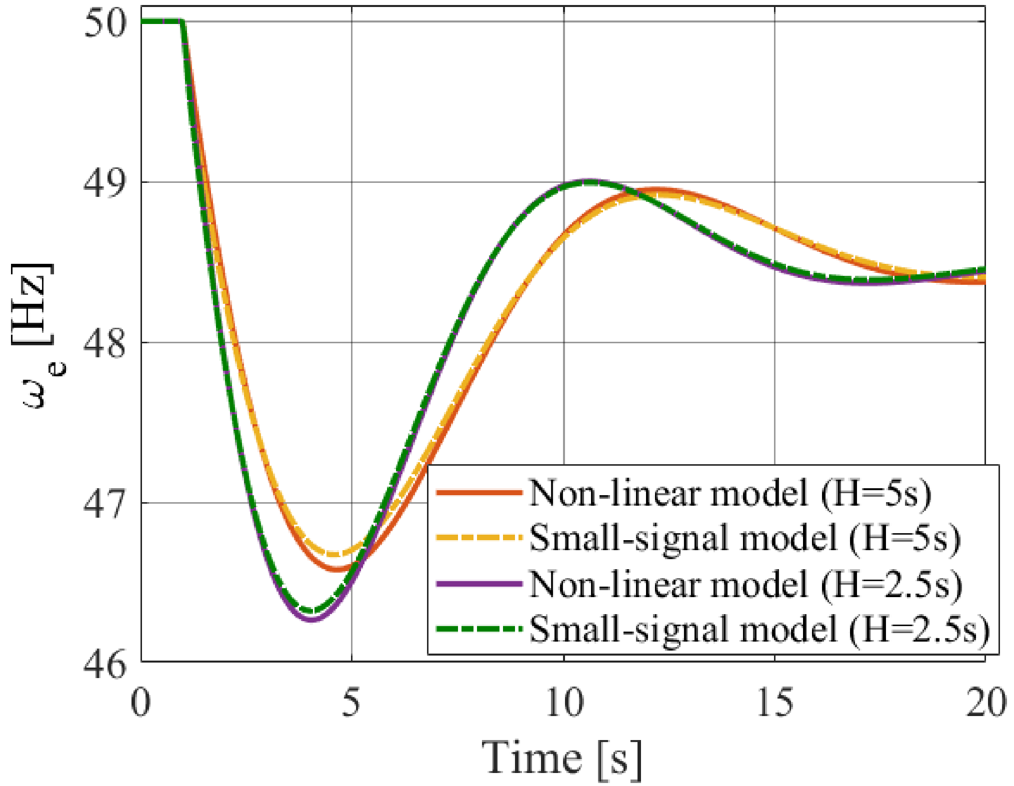


If the modulated frequency ω_m is assimilated to the grid frequency ω_e. Both inertia can be merged with respect to their own base power S_{b1}, S_{b2}

$$H_{eq} + H\frac{S_{b1}}{S_{b2}}$$

Simplified small signal stability model

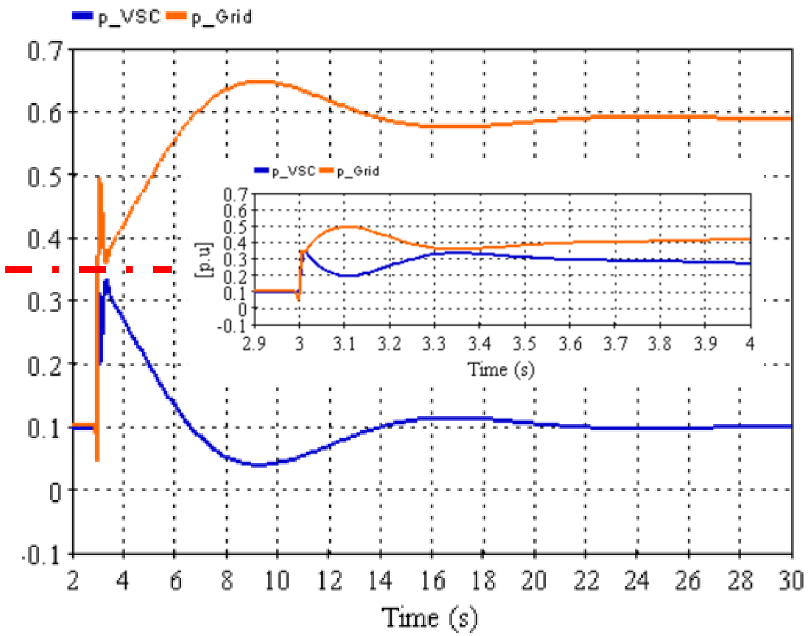




The dominant mode is well reproduced by the simplified model
This shows that the behavior of the grid forming converter in term of inertial effect is exactly the same as for a synchronous machine

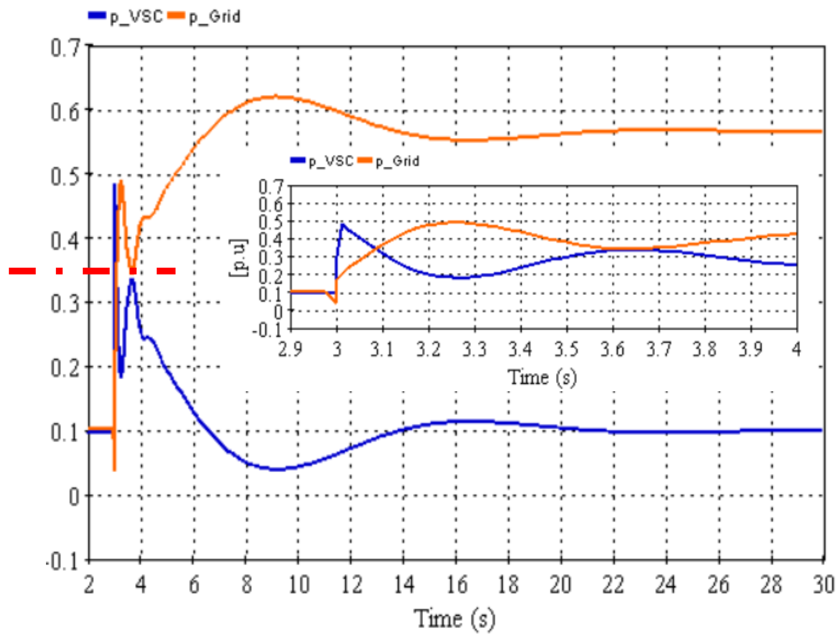
SCR = 5
H_{VSC} = 5 s
H_{eq} = 5 s

ΔP_{VSC}



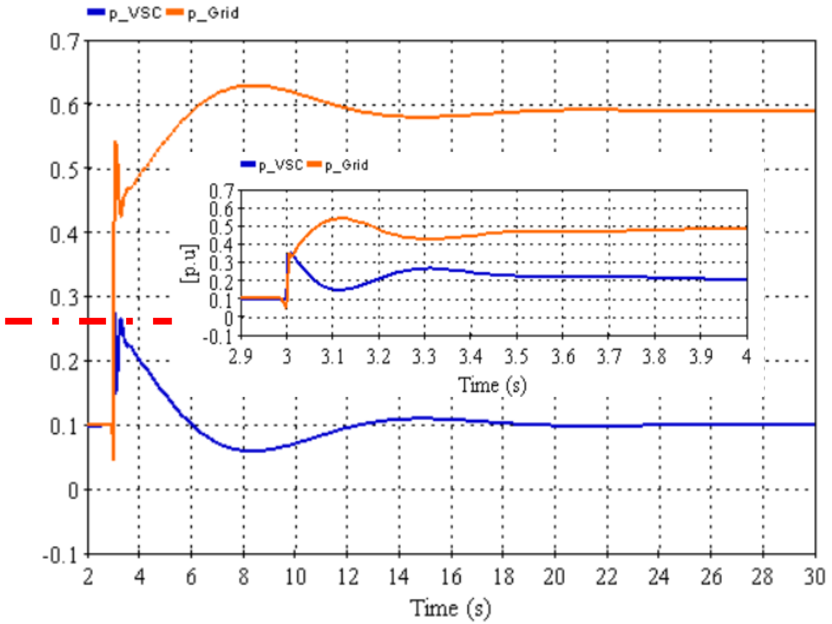
SCR = 1.3
H_{VSC} = 5 s
H_{eq} = 5 s

ΔP_{VSC}



SCR = 5
H_{VSC} = 2.5 s
H_{eq} = 5 s

ΔP_{VSC}



When zooming on the transient, it appears that :

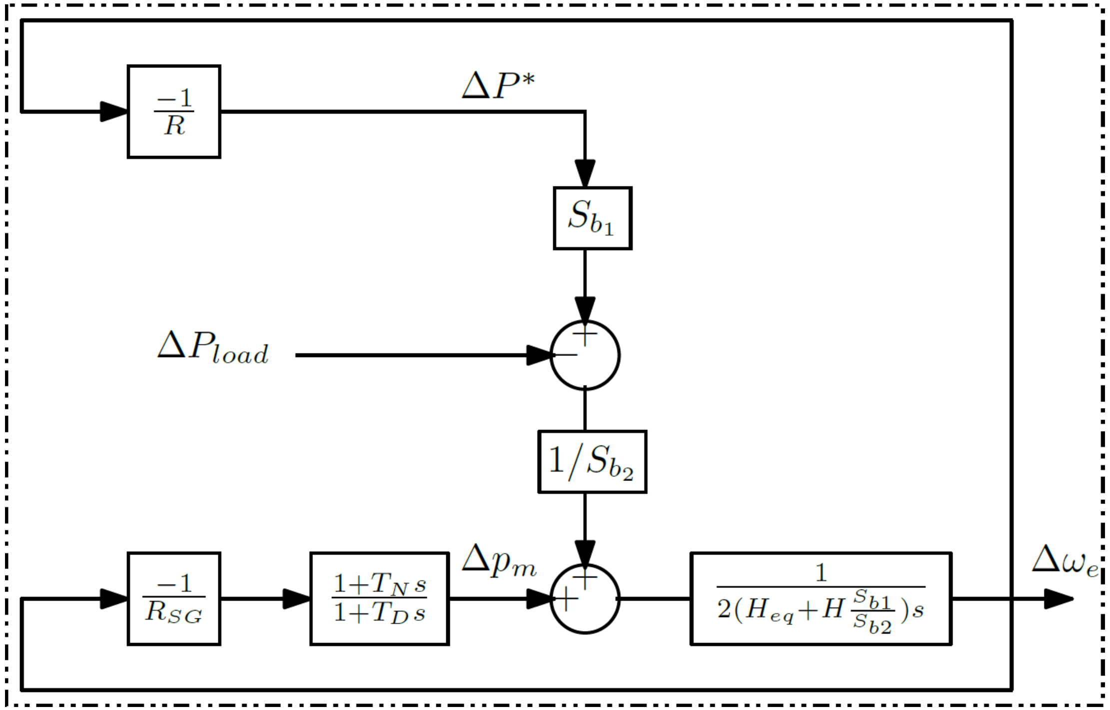
- The first peak depends on the impedance ratio (voltage source behavior)
- The second peak depends on the inertial effect

$$\Delta P_{load} = 2\left(H_{eq} + H\right) s\, \Delta\omega_e$$

$$\Delta P_{VSC} = 2\ \ H\, s\, \Delta\omega_e$$

$$\Rightarrow \quad \Delta P_{VSC} = \Delta P_{load} \frac{H}{H + H_{eq}}$$

When adding a frequency droop (*R*) on the active power reference, the simplified model is slightly modified

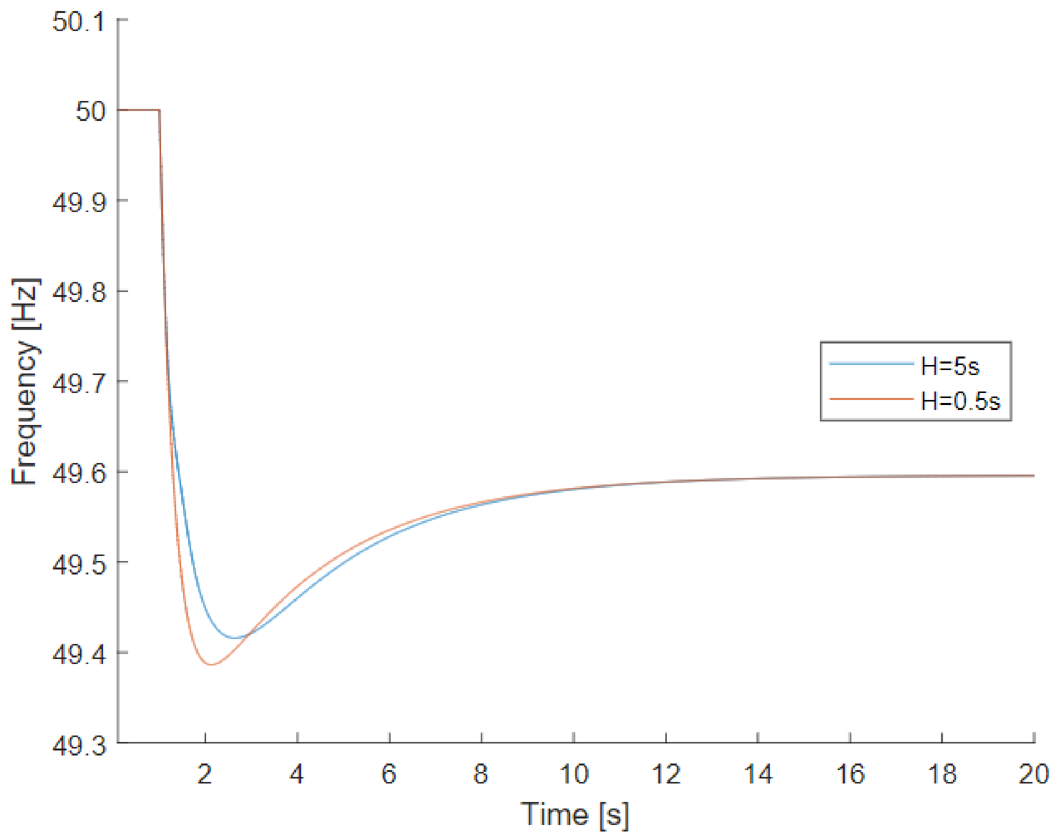


This model clearly highlights the difference between the action of the power converter and the classical power sources : The effect of the frequency variation on the power variation is nearly instantaneous

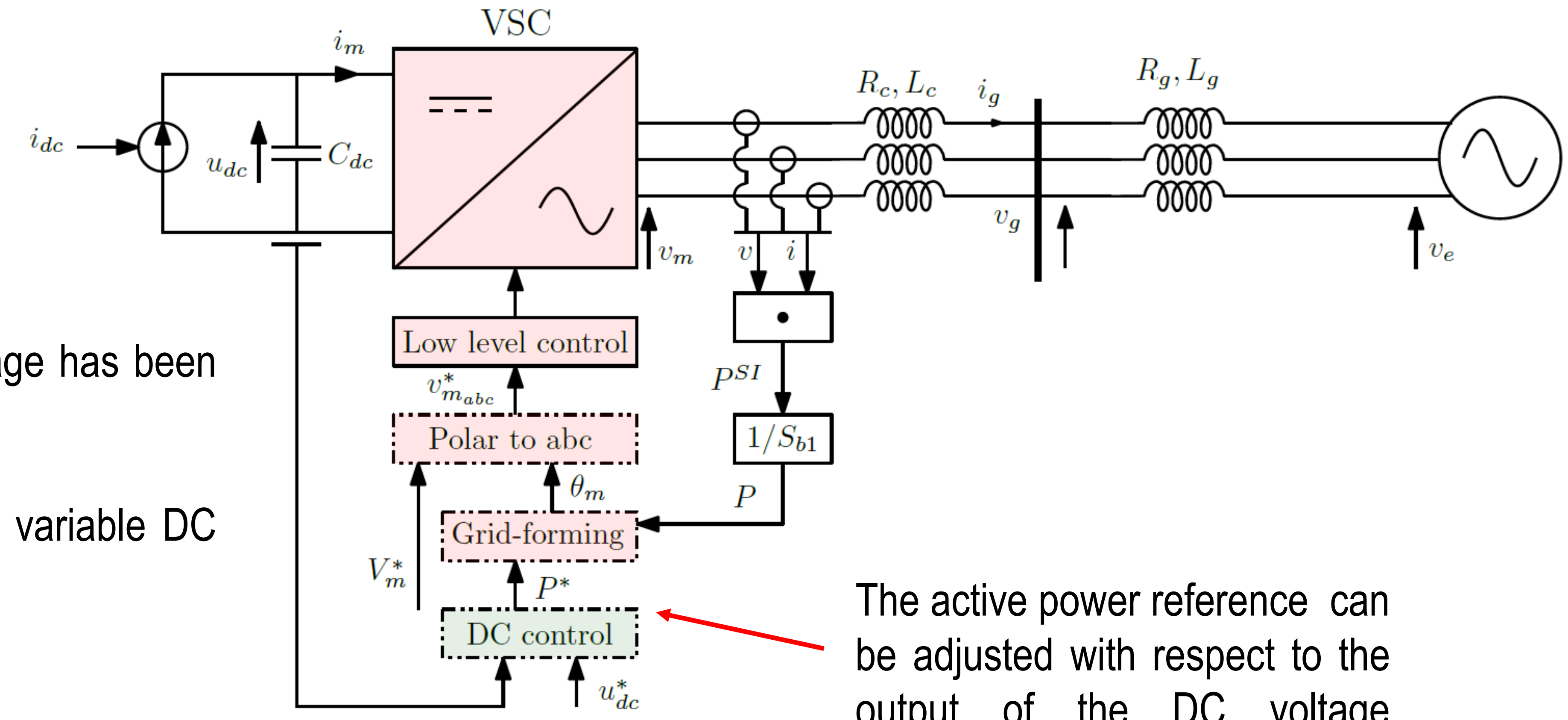
Where as in classical power sources, there is always the dynamics of the turbine which slowing down the variation of mechanical power.

Consequence :

The inertial effect of included in the grid forming power converter is much less important on the frequency dynamics than with a synchronous machine



Main applications for the grid forming control: HVDC link

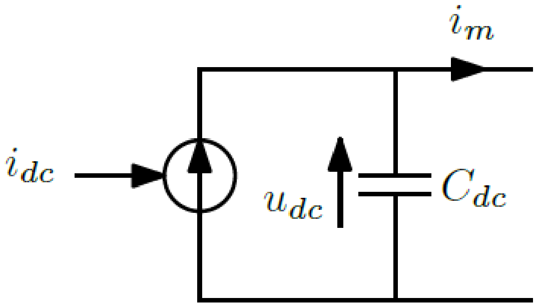


Till now, the DC bus voltage has been considered as constant.

What happens in case of variable DC bus voltage ?

The active power reference can be adjusted with respect to the output of the DC voltage controller

- DC bus model

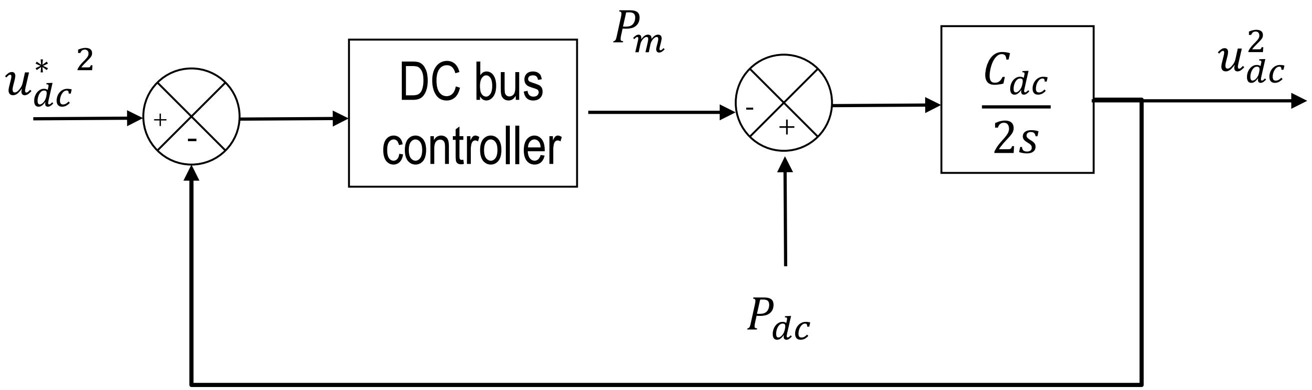


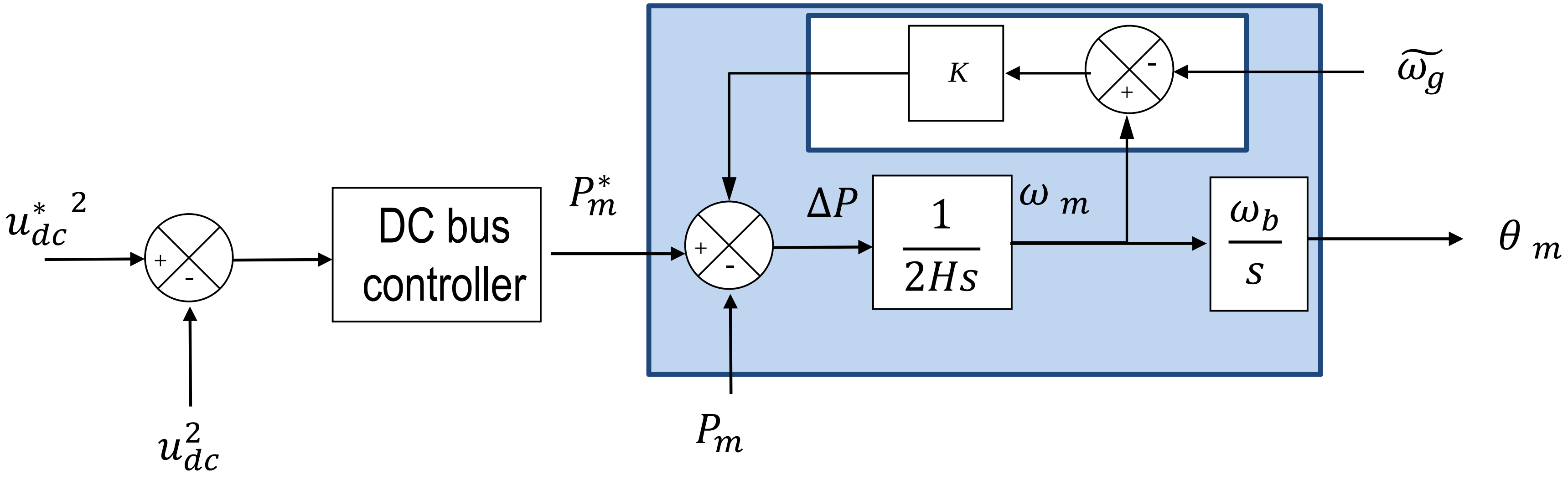
$$i_{dc} - i_m = \mathrm{C_{dc}} \frac{du_{dc}}{dt}$$

$$\Rightarrow i_{dc}u_{dc} - i_m u_{dc} = \mathrm{C_{dc}} \frac{du_{dc}}{dt} u_{dc}$$

$$\Rightarrow P_{dc} - P_m = \frac{C_{dc}}{2} \frac{du_{dc}^2}{dt}$$

- DC Voltage control



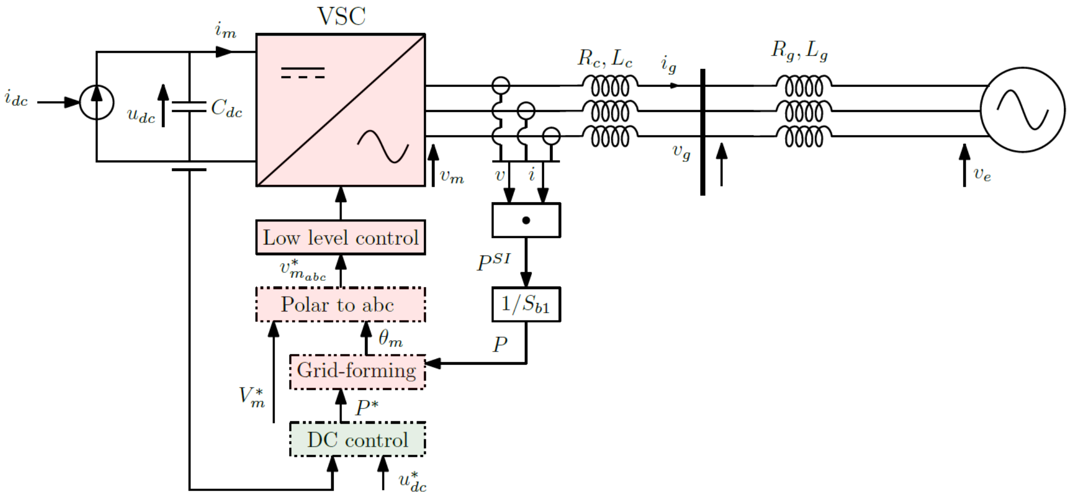


During a frequency transient both controls have a contradictory effect:

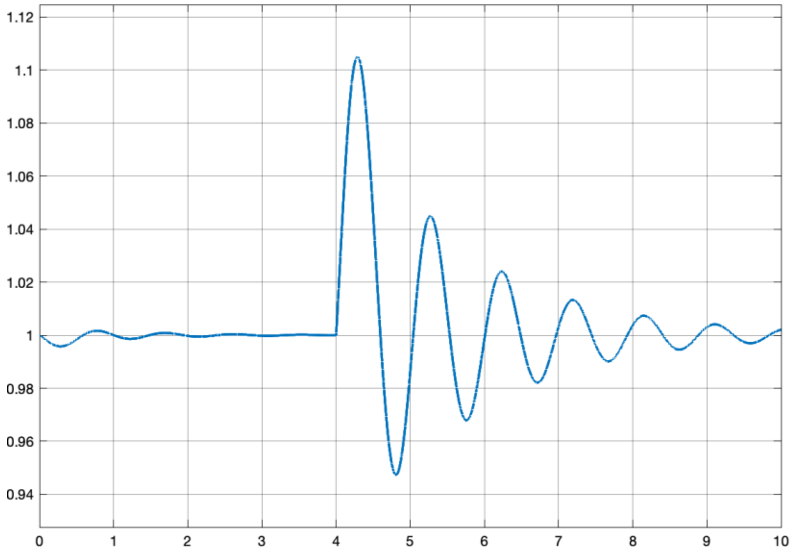
If the frequency decreases, P increases.

In the same time u_{dc} decreases, the output of the DC bus controller decreases P^*

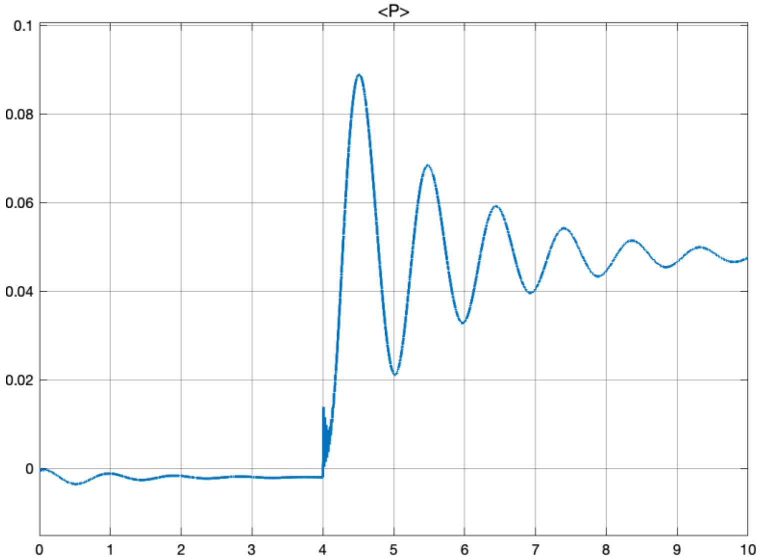
The DC bus control tends to counteract the inertial effect.



Udc



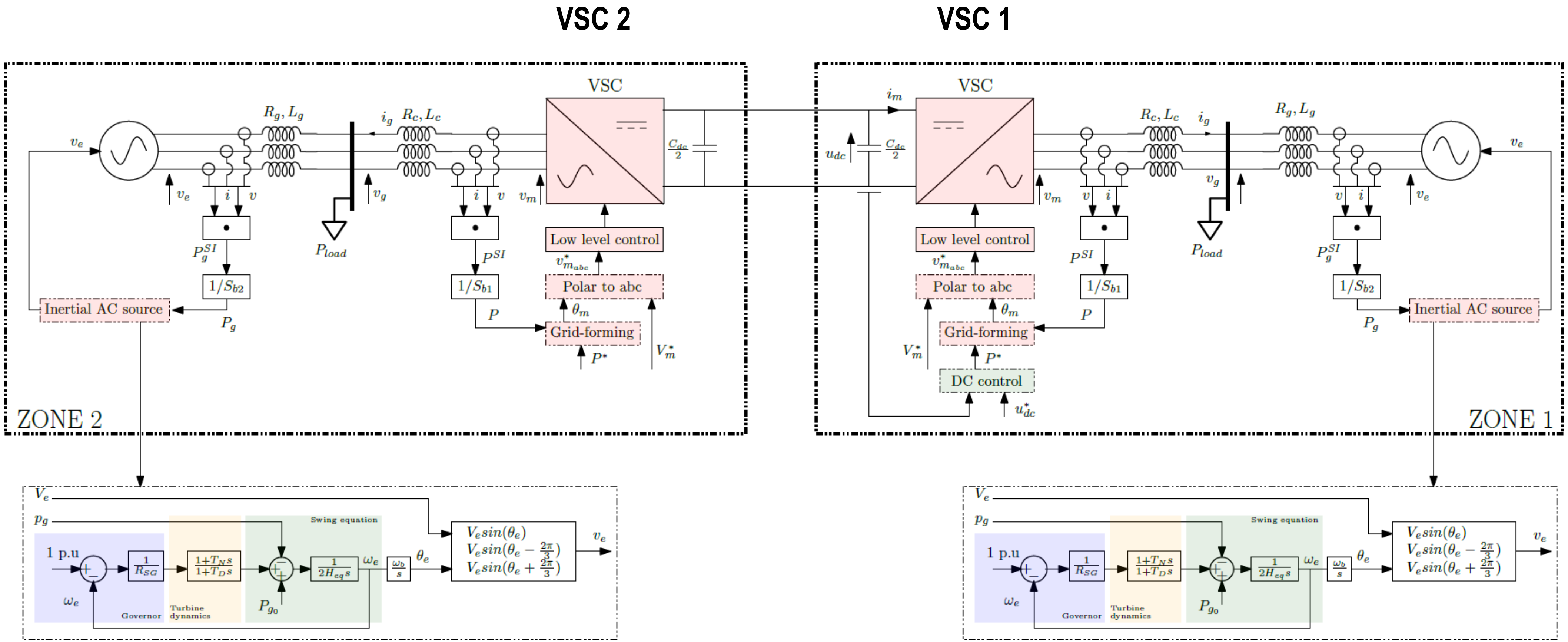
P

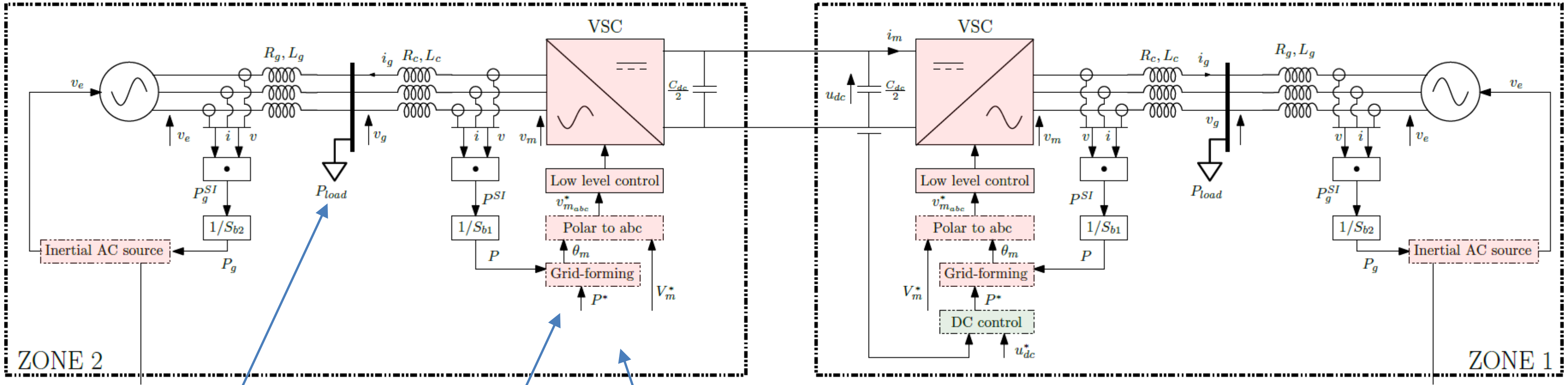


Conclusion : it is very difficult to control the DC bus voltage with a grid forming converter

VSC 2 is controlling the power flowing through the HVDC link : same situation as previously

VSC 1 is controlling the DC bus voltage

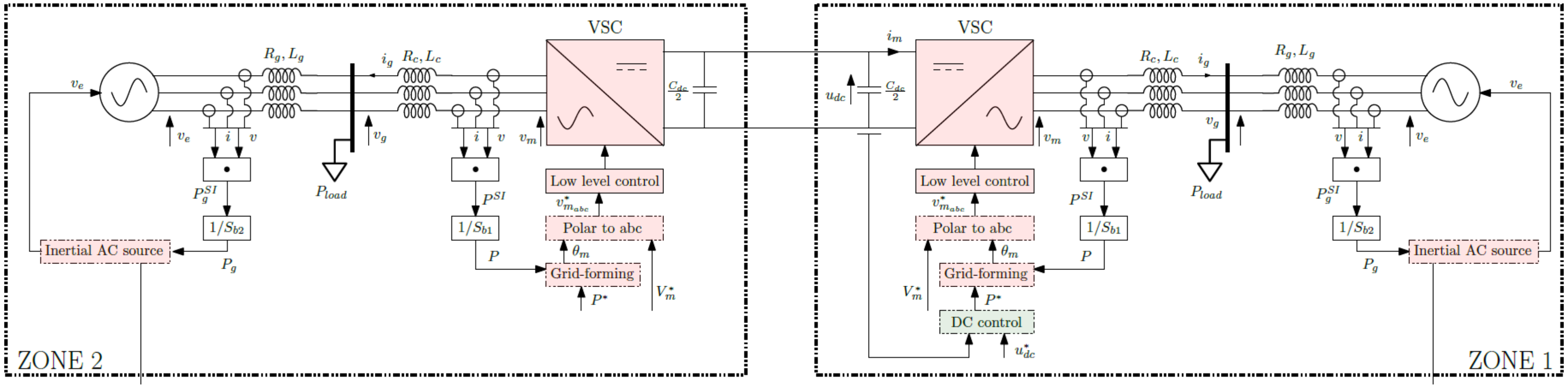




1st event : load variation

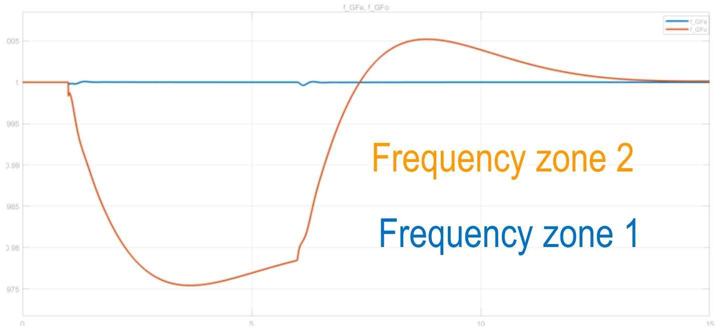
The frequency droop is disabled on the grid forming control. Constant power reference

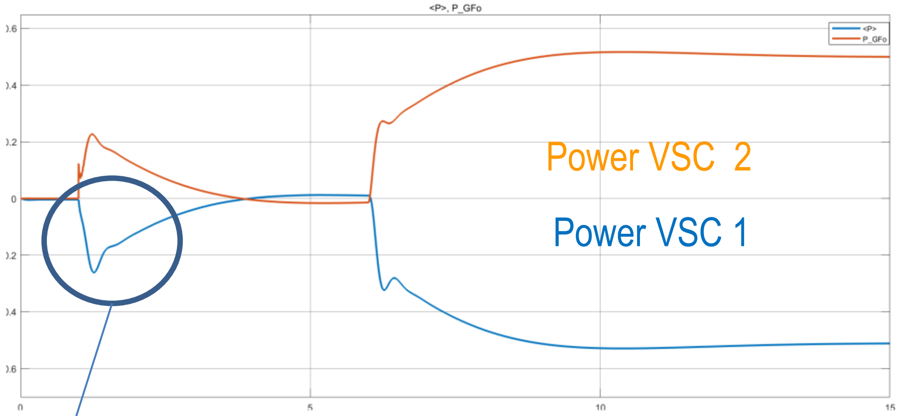
2nd event : a step is applied on the power reference



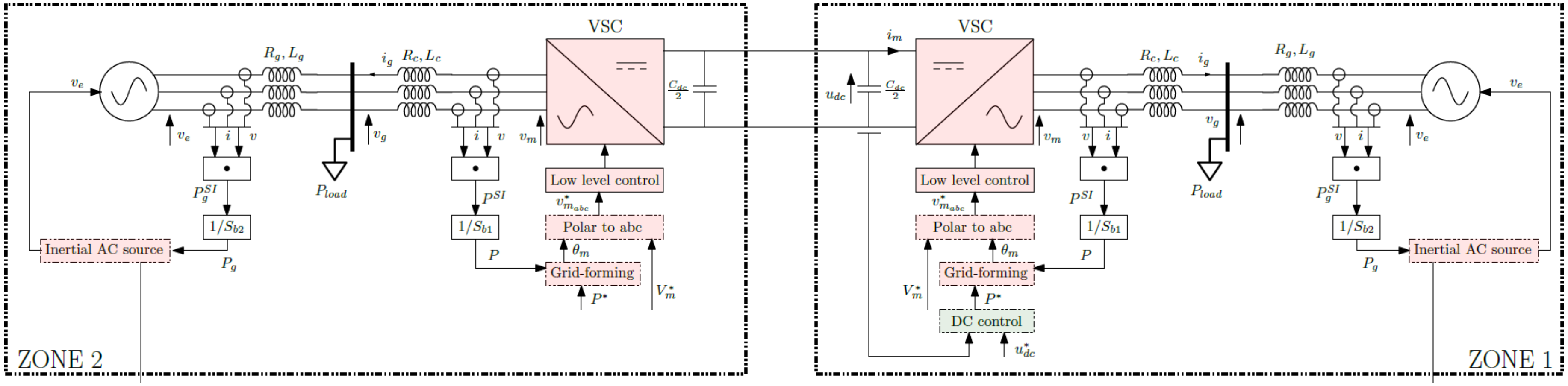
1st event : load variation

Frequency decrease

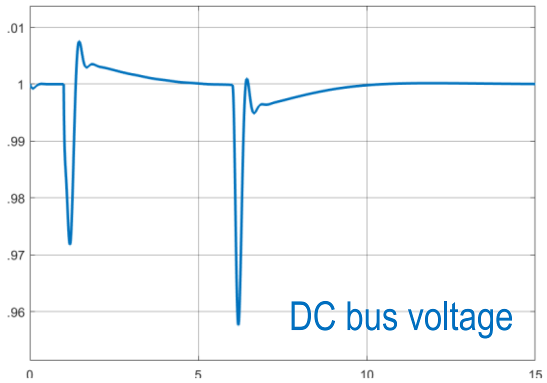


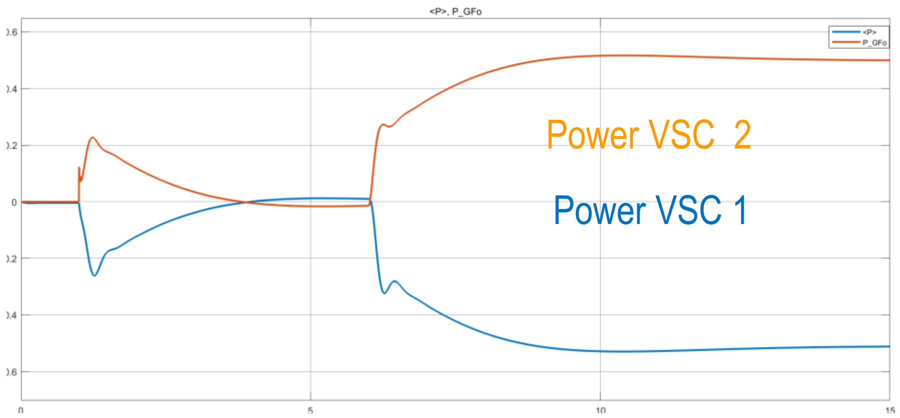


Inertial response from the grid foming converter



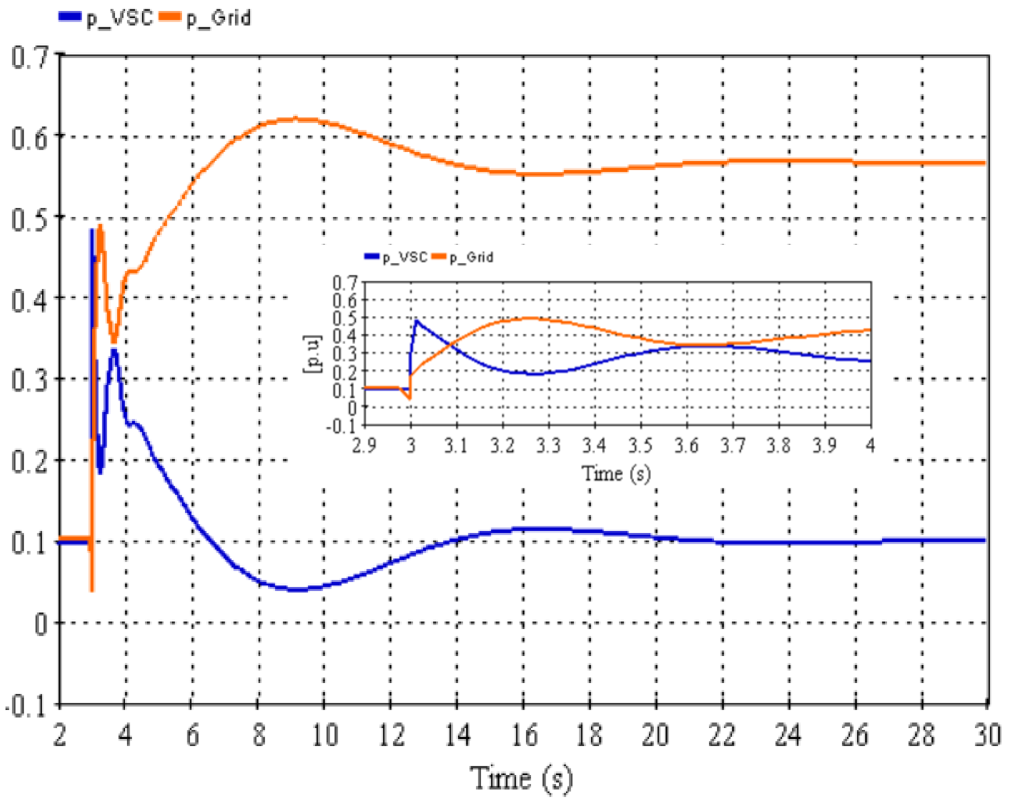
As in a classical HVDC link the power is adjusted thanks to the DC bus control





Some thinking about the headroom and required energy for a grid-forming application

Inertial effect in case of a frequency variation

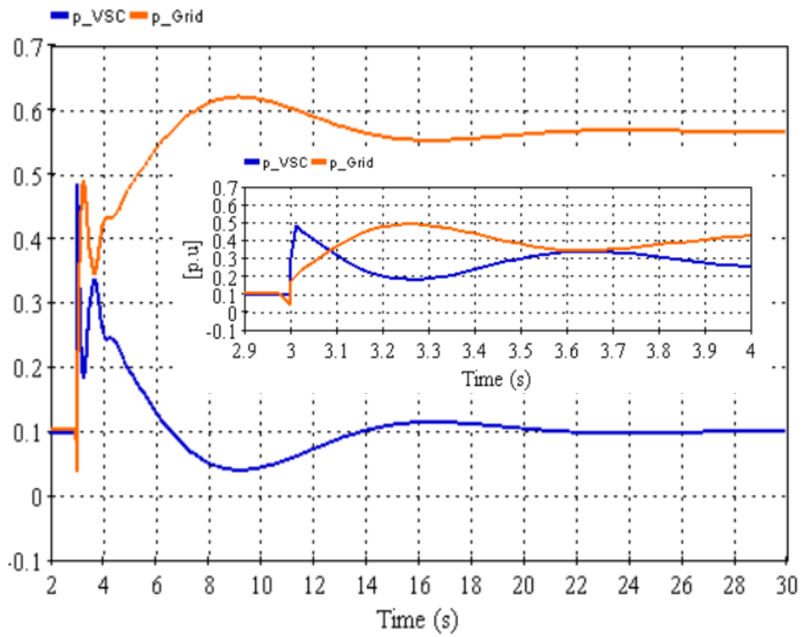


As already mentioned, the first peak depends on the grid strength at the PCC, the second peak depends on the inertial effect

The first peak can be removed, if needed by the current limitation without nearly no influence on the frequency dynamics

It will have an influence during a very short transient on the voltage at PCC.

Inertial effect in case of a frequency variation



As already mentioned, the first peak depends on the grid strength at the PCC, the second peak depends on the inertial effect

Since the second peak it linked with the inertial effect. It cannot be removed.

$$\Delta P = 2\,H\,\frac{\Delta\omega}{\Delta t}$$

The headroom to take into account depends on the acceptable ROCOF and the expected value for the inertia .

The extra energy can be provided either at the DC bus level by integrating an energy storage or by any other converter connected on the same DC bus. .

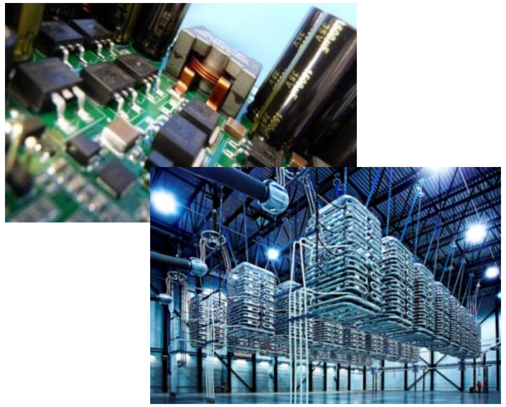
System Level Integration of Grid Forming Capabilties

02.07.2021

Dr. Mario Ndreko

Background

More Power Converters



On generation side, a massive installation of power converters based power sources throughout the distribution and transmission system

On the demand side, similar trends are being observed with the load being increasingly interfaced with power converters, e.g. industrial motors or EVs

On the high voltage transmission system, increased HVDC transmission capacity is expected by 2030 (70GW embedded HVDC links)

*different power system **dynamic profiles***

primarily caused by the **displacement of the synchronous generation** fleet

secondarily caused by the **faster time constants introduced by power electronic converters** and actuators compared to SG dominated grids

Stability Challenges

TSOs View on Power System Stability Challenges

The EU-Horizon-2020 funded project **MIGRATE conducted a survey among 21 European TSOs aimed at identifying power system stability challenges** as perceived by the industry under high penetration of PEIPSs.

Ranking	Score	Issue
1	17.35	Decrease of inertia
2	10.16	Resonances due to cables and Power electronics
3	9.84	Reduction of transient stability margins
4	8.91	Missing or wrong participation of PE-connected generators and loads in frequency containment
5	8.19	PE Controller interaction with each other and passive AC components
6	7.50	Loss of devices in the context of fault-ride-through capability
7	7.00	Lack of reactive power
8	6.91	Introduction of new power oscillations and/or reduced damping of existing power oscillations
9	6.09	Excess of reactive power
10	4.27	Voltage Dip-Induced Frequency Dip
11	3.87	Altered static and dynamic voltage dependence of loads

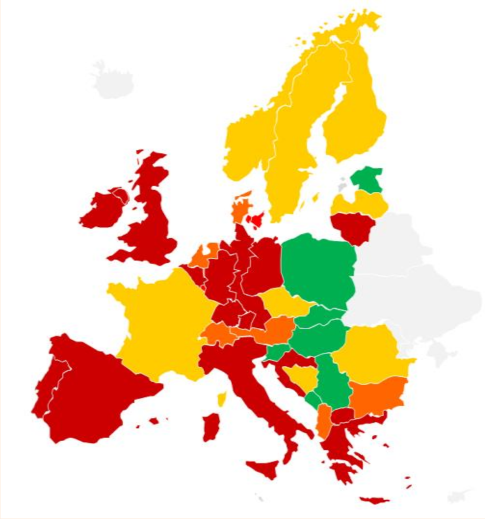
A recent report from the sub-group **System Protection and Dynamics (SPD) working group of ENTSO-E** has ranked the increase of **RoCoF as a top power system stability challenge** for the CE system in 2040+

Situation in Europe by 2030

Total System Inertia

Today: For the **normal interconnected operation** of the CE power system, **the inertia is sufficient considering the normative loss of 3GW**

2030 Scenario:
The **national per unit TSI constant H sometimes falling below 2 s is of concern,** compared with a traditional value of about 5–6 s



Inertia contribution colouring code:

- Green — H ≥ 4 s — Very good contribution
- Yellow — 3 s ≤ H < 4 s — Good contribution
- Orange — 2 s ≤ H < 3 s — Marginal contribution
- Red — H < 2 s — Limited contribution

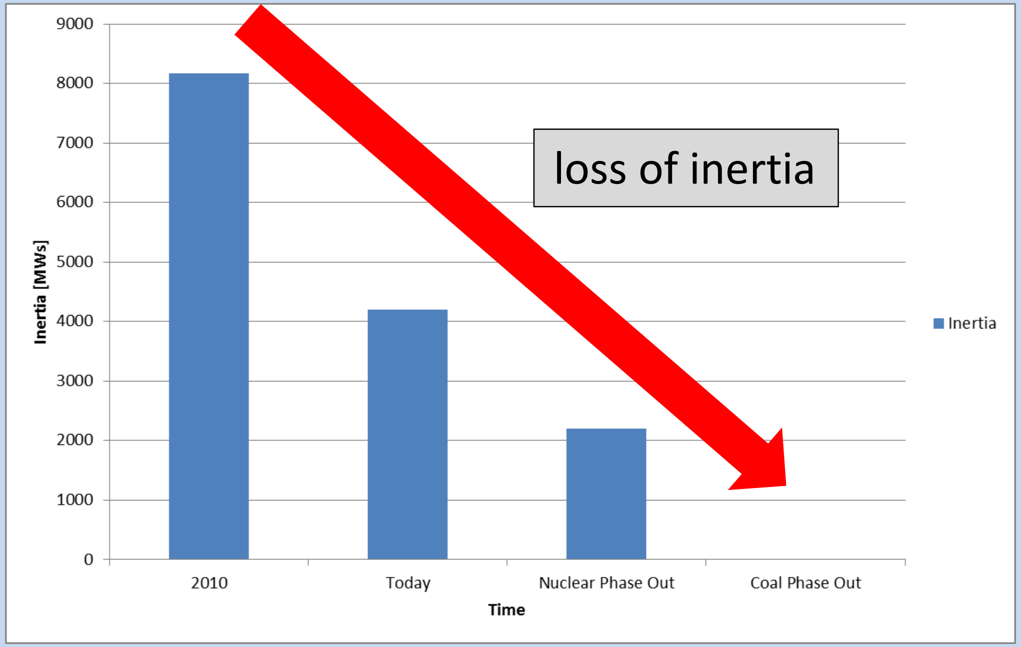
At least **two SAs, GB and Ireland, and a number of individual countries' contribution within CE are expected to fall within this category**, highlighting their need to prepare their strategy to cope with such grid conditions

System Split: Today a 20% imbalance in the continental European system with a RoCoF of 1 Hz/s is identified as critical and can drive the system to unpredictable states. In Germany 2 Hz/sec and up to 40% imbalance identified!

Inertia at TenneT Control Area

Calculation of inertia of huge power plants (> 100 MW) connected in TenneT Germany area

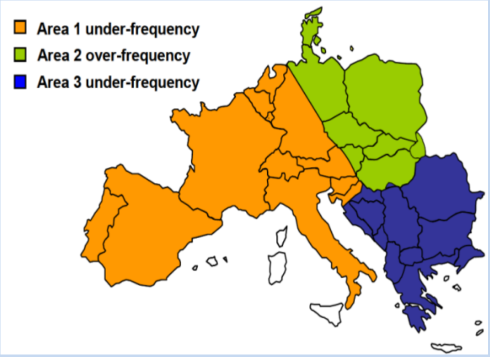
- **loss of approx. 4000 MWs of rotational energy *** due to power plant shutdowns in the TenneT-D control area in recent years
- due to phase-out of the last three nuclear power plants in TenneT area further loss of app. **E_{ROT} = ca. 2000 MWs* by end of 2022**
- **in total: loss of > 8000 MWs inertia in TenneT-D control area**



*if assuming a frequency change from 50 Hz to 47,5 Hz

Frequency Stability

System Separation (split)



System split is identified as **a grid extreme contingency leading to separation of the system** into asynchronous zones.

Rare events such as **system splits** (currently experienced once in decades), becomes **critical under high penetration levels** of renewable generation sources.

Exports and imports before the system split event become **power imbalances** for the separate islands after the split.

A **system split is more likely** to occur across **highly loaded weak transmission corridors**.

The **potential imbalance after a rare system split which the systems need to survive is expected also to increase**, bringing the system to its **physical limits** in terms of balancing capability.

Developments of the **European Electricity Markets are leading to the transit flows** gradually increasing in magnitude, making system split cases in future more difficult to handle.

Frequency Stability

The most common remedial actions are LFDD, LFSM-U and LFSM-O.

20% imbalance in the Continental European Synchronous are results in 0.5-1.0 Hz/s RoCof

If frequency deviations exceed 47.5Hz or 51.5Hz, a black out can hardly be avoided (Power Generation units will trip below 47.5Hz)

20% imbalance with 1Hz/s is critical and can drive the system to unpredictable states

Market simulations for the future ask for **40% imbalance and 2Hz/s** withstand capability

Future Electrical System Design

The System must **cope with cases of split with imbalances of greater than 40%** leading to RoCof greater than 2Hz/s

- Under-frequency load shedding below 49Hz in the under-frequency island is needed
- power reduction of generation units in the over-frequency island

Normative incident of system split consists of:

- **Maximum imbalance** (as a percentage of the load in the system)
- **Maximum RoCof** or minimum required inertia

LFDD can be ineffective when inertia is low and power deficit is high

- As an example, in Australia, AEMO has determined that **ROCOF must be less than 3 Hz/s** to allow LFDD to operate effectively
- **inertia should be maintained** to ensure this for all secured events (i.e. excluding system splits).
    - the RoCof observed during the Australian black-out event was 6 Hz/sec

Short Circuit Power Levels

Effect of reduction

Deeper voltage drops (in the medium and low voltage network) **and more widespread (in geographic area)** in the event of severe transmission network faults.

Loss of devices in the context of fault-ride through capability. Clearly, **outages of such nature would affect the frequency stability** and would have a more global system effect **under high penetration of PEIPS**.

With regard to **PEIPS, it is well known that their stable and robust operation is affected** significantly by the correct operation of the **phase-locked loop (PLL)** modules.

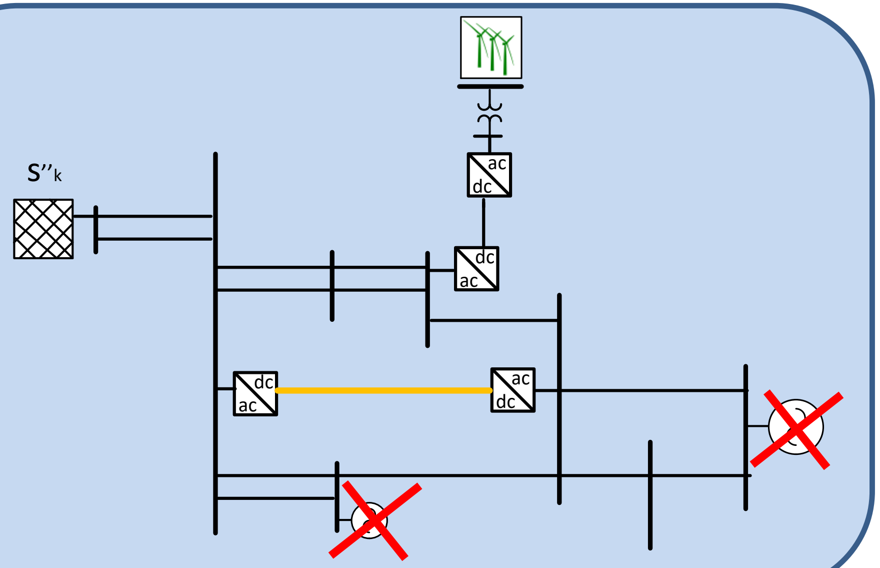
In weak grid connection environment, the stable and robust operation of the **PLL along with the application of vector current control loops (grid following)** could be a potential reason for PEIPS instability.

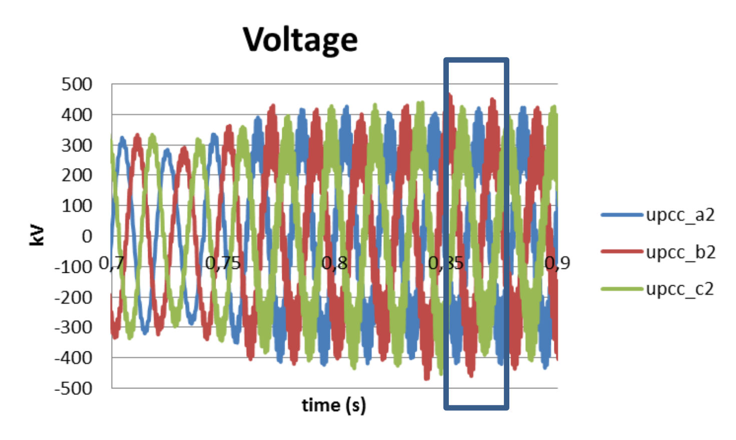
Main Operation Challenges due to massive penetration of PEIG

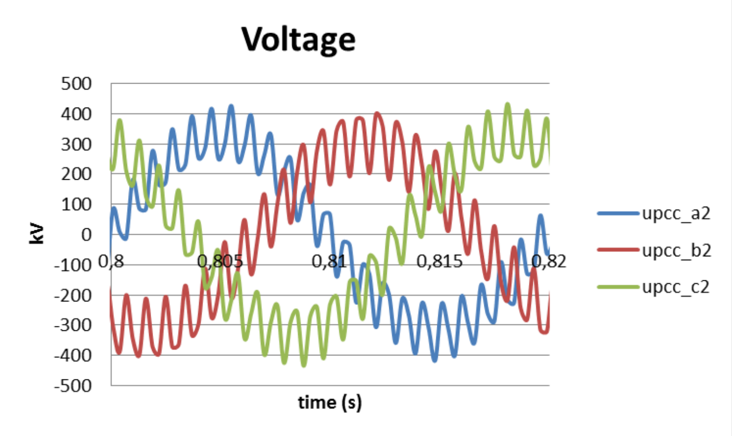
Control Interactions

Example:

The reduction of short circuit power levels (**Sk”) as a result of disconnection of conventional power plants** could trigger control oscillations between HVDC and grid.







Inverter Based Power Plant Modules (PPMs) and HVDC Converter Stations: Today

Class 1 PPMs / HVDC Converter Station

- Full frequency operating range
- Full voltage operating range
- Basic reactive controls – e.g. Unity Power Factor
- LFSM-O
- Complies with local power quality requirements (e.g. harmonics / unbalance current)

Class 2 PPMs / HVDC Converter Station

- Fault Ride-Through
- Voltage control – steady state
- Voltage control – dynamics
- Voltage control – at P=0
- FSM
- LFSM-U
- Provides damping
- Fast Fault Current Injection (FFCI; see IGD)

- **Issues / challenges potentially remaining even with Class 2 converter capabilities**
- **If PEIPS penetration moves beyond 60% towards 100% of instantaneous power demand**

Inverter Based Power Plant Modules (PPMs) and HVDC Converter Stations: Future

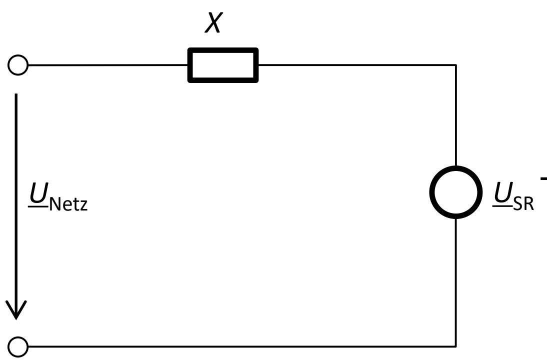
Future capabilities provided by PPMs and HVDC station in order to allow close to 100% instant penetration of RES in a synchronous area

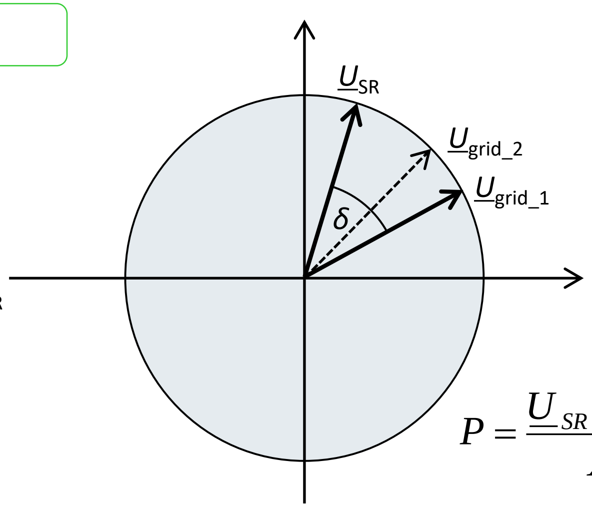
1. Creating **system voltage**
2. Contributing to **Fault Level**
3. Contributing to **Total System Inertia** (limited by energy storage capacity)
4. Supporting system **survival to allow effective operation of Low Frequency Demand Disconnection (LFDD)** for rare system splits.
5. Acting as a **sink to counter harmonics & inter-harmonics** in system voltage
6. Acting as a **sink to counter unbalance in system voltage**
7. Prevent **adverse control system interactions**

Grid forming vs. grid following

- step on voltage angle (frequency change)

grid forming

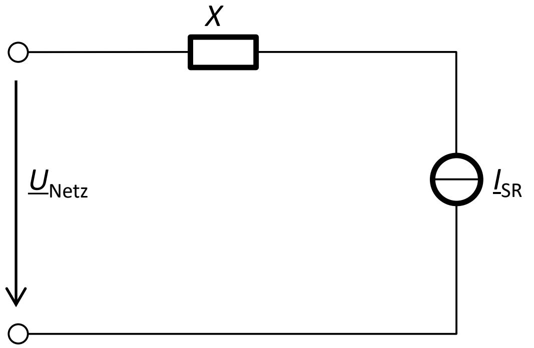


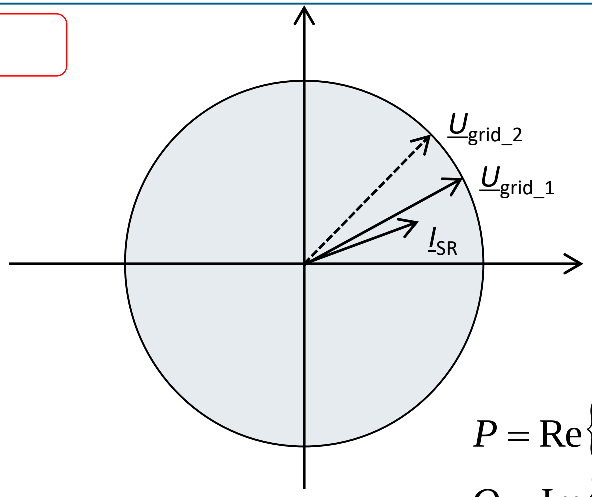


- ➢ "inner voltage" (control voltage, $\underline{U}_{SR}$) of PEIPS constant (like synchronous inner voltage of generators)
- ➢ exchange of P (and Q) dependent of X and angle (not of energy source!)
- ➢ instantaneous, inherent frequency support (without measurement)
- ➢ superordinate P(f)-droop control

$$P = \frac{\underline{U}_{SR}\underline{U}_{Netz}}{X}\sin\delta \xrightarrow{P*t} \textbf{Energy}$$

grid following





- ➢ immediate change of control voltage of PE
- ➢ current is controlled to be constant to keep feeding in all power coming from the primary source constant
- ➢ determine f through the PLL (measurement!)
- ➢ superordinate P(f)-droop control

$$P = \mathrm{Re}\left\{\underline{U}_{Netz}\,\underline{I}^{*}_{SR}\right\}$$

$$Q = \mathrm{Im}\left\{\underline{U}_{Netz}\,\underline{I}^{*}_{SR}\right\}$$

Only Grid Forming provides true Inertia

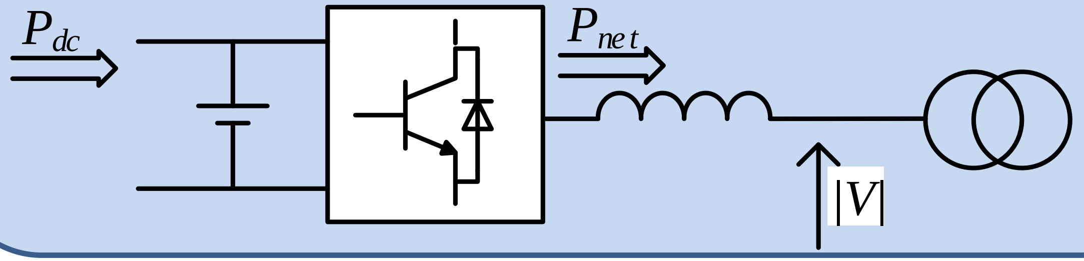
Because Grid Forming Converters:

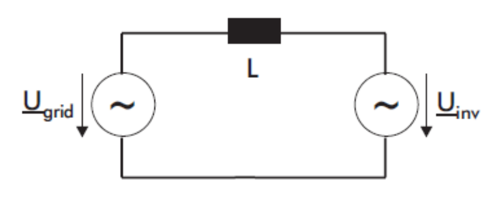
- behaves as true voltage source behind impedance
- the active power is exchanged naturally with the grid as a result of the angle displacement

Note: Grid Forming Converters need energy buffer

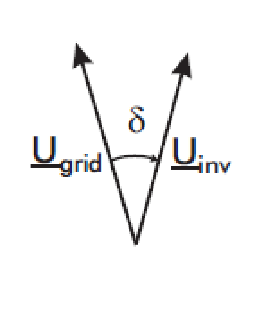
Normal operation: $P_{net}=P^*_{conv}=P_{dc}$

Inertial response: $P_{net}=P^*_{conv}+P_{Disturb}=P_{dc}+P_{Refill}$





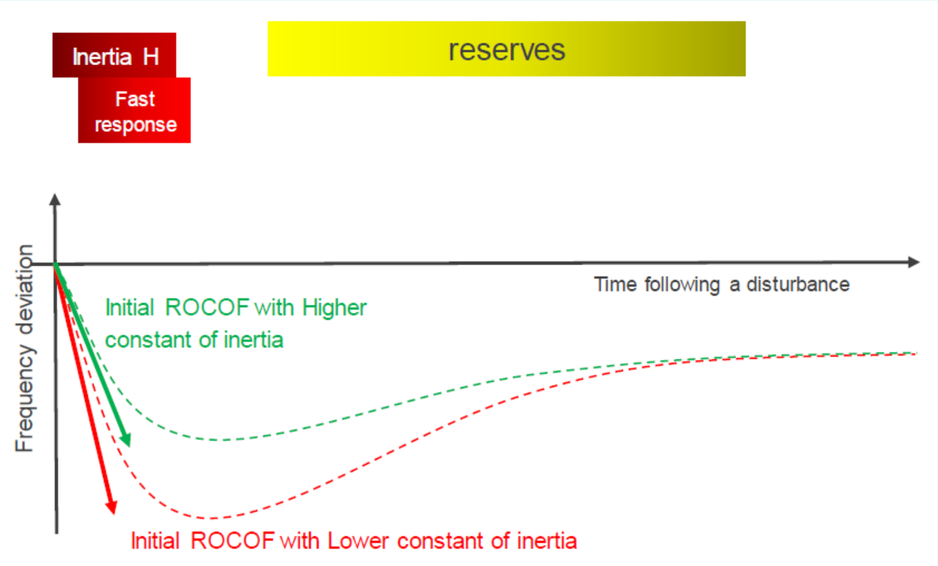
equivalent circuit



phasor diagram

MW*s

Grid forming vs. grid following



A Synchronous machine or a synchronous condenser will limit the initial RoCoF inherently!

Grid Following

1. Measure frequency
2. Process measurement
3. React and change power

Slow does not limit the Initial RoCoF

Grid Forming

Due to voltage source behavior reacts instantly

Limits the Initial RoCoF

Responsibilty of TSOs

- **TSO assets** (which will be installed due to other reasons) where it is technically feasible **shall be enabled to contribute to inertia** in future
  - **no preference about specific technology**
  - mixture of different solutions, i.e. STATCOM, synchronous condensers with fly wheels dependent of other grid needs
  - <u>increase TRL needed for all potential technologies</u>

- **All Grid users need to contribute to system**
  - TSOs define the system needs
  - National Implementation of NC HVDC in Germany (TAR 4131) requires this capability for all new connections commissioned after Sep. 2018

What the market can provide today?

Experience with GFC up to date is limited

GFC has so far been established in applications (mainly in **microgrids**) where it is required to ensure stable system operation already today

So far the most common grid connected adoption of GFC control is associated with BESS facilities mainly linked to PV installations.

- From a few MW, so far up to a 30MW installation in South Australia.

HVDC systems can today offer grid forming capabilties

For wind, the reported installations so far are limited to only test sides.

- 23 turbine 69MW wind farm on test with GFC for 8 weeks with H up to 8s (Siemens-Gamesa)

Conclusion:

- GFCs have not yet been established by the major wind turbine manufacturers in their mass market converter products.
- PV and HVDC system manufactures are ready to provide solutions.

Size of energy storage needed?

Assumptions

/ System Split Scenario of 2006
/ 50% of all connected assets contribute to inertia
/ max. RoCoF = 2 Hz/sec (system emergency functions are not designed for higher RoCoFs!)
/ transits acc. to Network development plan up to 40 GW

→ assets, which contribute to inertia (50%), shall contribute to inertia with 1pu*s/pu

→ if less assets contribute it has to be taken over by the rest
→ higher energy provision necessary!
→ growing transits and/or higher requirements to RoCoF lead to higher contribution

Cost?

Based on recent studies [1], overall costs between Grid-Forming (GFC) and Synchronous Condensor (SC) based solutions are within the same order of magnitude

mixture of different technologies (SC, GFC STATCOMs, GFC Wind, etc.) most constructive!

- <u>Cost Benefit Analysis (CBA) [1]</u>

➢ assumptions based on ENTSO-E policy for Load-Frequency Control for island operation of France
  - ➢ good comparison to Germany regarding size of country (and electricity system)
  - ➢ forecast time: 2035 (in Germany: date of phase out of last coal plants)

➢ comparison between two scenarios based on forecast simulations for France
  - ➢ „low-tech“ → stability ensured by SC
  - ➢ „New Regulation“ → stability ensured by GFC with storage

[1] Paper: Future grid stability, a cost comparison of Grid-Forming and Synchronous Condenser based solutions. EPE’20 ECCE Europe.

ENTSO-E Position

ENTSO-E Position1

Motivation

Grid forming requirements need to be defined in connection network codes in order to enable harmonised solutions across Europe

Harmonised requirements to be available throughout European member states (preferably mandatory but also possible as non-mandatory or part of the prequalification requiremetns of ancillary services).

Reference for more reading: https://eepublicdownloads.entsoe.eu/clean-documents/RDC%20documents/210331_Grid%20Forming%20Capabilities.pdf

ENTSO-E Position

ENTSOE Position2

Motivation

Developing sufficient conditions for grid forming capabilities via national level ancillary services

The regulatory authority of each country has to decide whether a market-based procurement is seen as economical beneficial or not, having the right to suspend such a market on the national level.

Reference for more reading: https://eepublicdownloads.entsoe.eu/clean-documents/RDC%20documents/210331_Grid%20Forming%20Capabilities.pdf

ENTSO-E Position

ENTSOE Position3

Motivation

New HVDC systems, FACTs and Synchronous Condensers could be the immediate candidates to explore the development of the grid forming capabilities

TSOs could initiate and accelerate the development of grid forming capabilities by specifying new HVDC systems, new FACTs and SCs. There is naturally a cost and regulatory dimension in this aspect which will trigger further interactions with the regulators on national level.

Reference for more reading: https://eepublicdownloads.entsoe.eu/clean-documents/RDC%20documents/210331_Grid%20Forming%20Capabilities.pdf

ENTSO-E Position

ENTSOE Position4

Motivation

Demand, storage and sector coupling facilities should be further explored in order to unlock their full potential of providing grid forming capabilities

- Storage facilities could play an important role in delivering grid forming capabilities.
- Sector coupling facilities could also provide such grid forming capabilities depending on the total installed capacity per country. Finally, hybrid power plants could be a future option that should not be neglected and further explored.

Reference for more reading: https://eepublicdownloads.entsoe.eu/clean-documents/RDC%20documents/210331_Grid%20Forming%20Capabilities.pdf

Conclusion and perspectives

Conclusion

This results shows that with very simple controllers (integrator, proportionnal action), it is already possible to have very effective controls which meets the main requirements which could be asked such as : good tracking of the active power in steady state and inertial effect, voltage ride-through capability

In simulation, it is possible to have a clear characterization of the inertial effect when the converter is not participating to the DC bus regulation otherwise there are strong interactions.

It is possible to limit the current and manage a re synchronization with no external signals

All the considerations which have been developed on an ideal VSC have been implemented on a 2 level VSC or MMC with no fundamental difference.

With this definition of the grid forming converter, it is possible to have a clear comparison with the synchronous machine.

What is similar ?	The way to synchronize
What is different ?	All the parameters can be modified on the fly The system is much more damped (not presented in this presentation) The current limitation is very different and the transient stability can be enhanced thanks to the control

All the simulation models are in Open access on github : https://github.com/l2ep-epmlab/

Perspectives

Interaction between DC bus control and grid forming

Still quite a lot of work about the enhancement of the transient stability by using different degrees of freedom provided by the control.

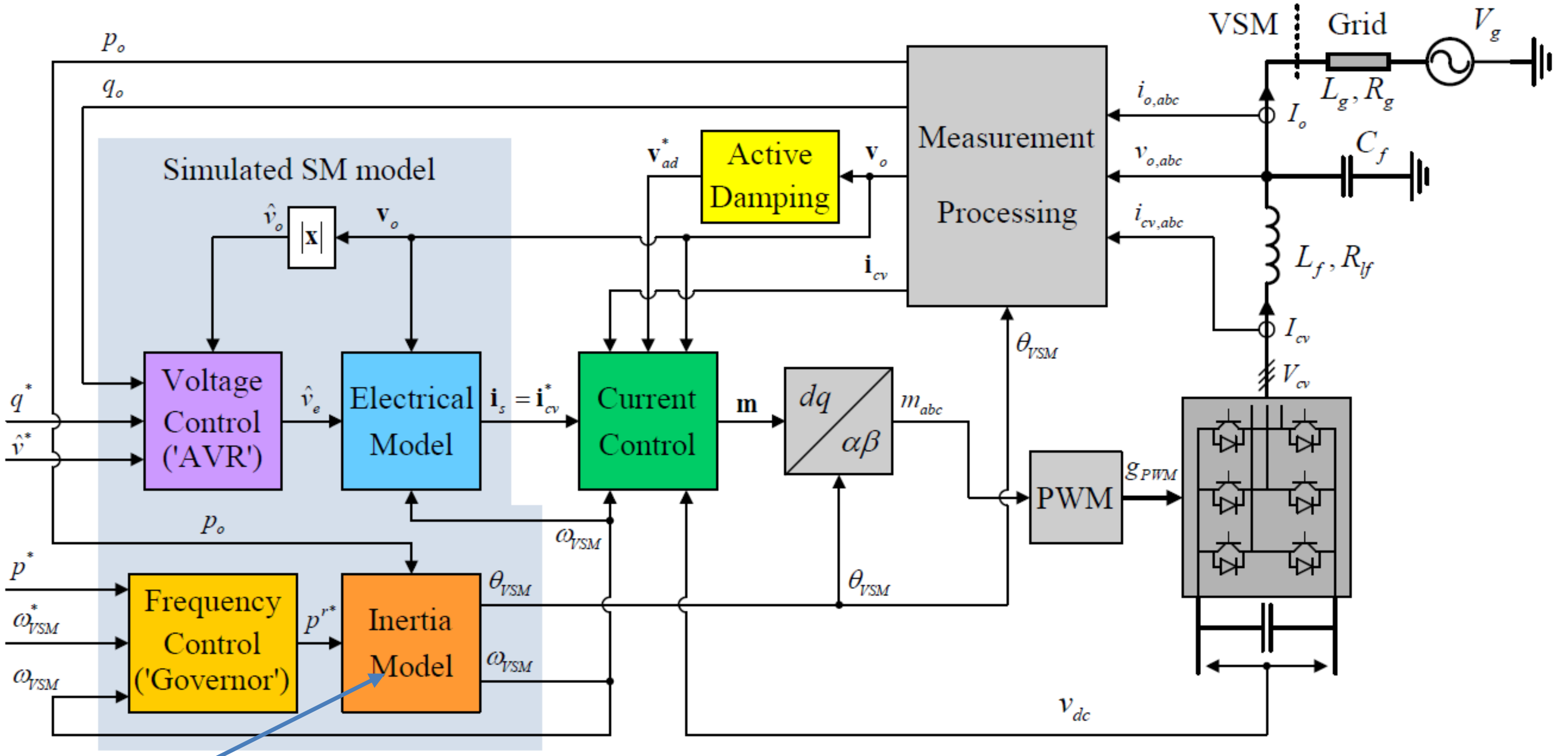
Current limitation in case of unbalanced situation

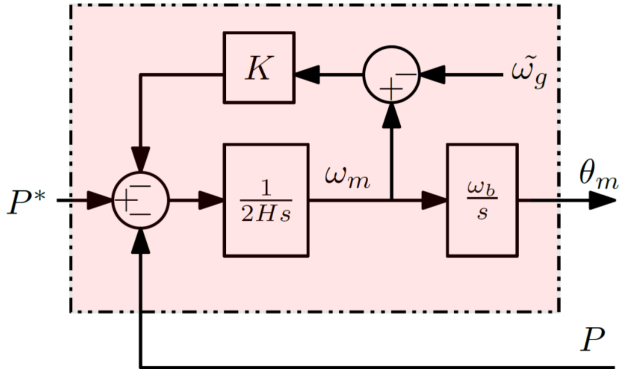
Comparison with another type of grid forming control where the current loop is always in operation.

Comparison between

a voltage source grid forming control as presented here

a current source grid forming control as presented below : same way to synchronize but the current loop is always under operation





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[1] "*Critical clearing time determination and enhancement of grid-forming converters embedding virtual impedance as current limitation algorithm"* IEEE Journal of Emerging and Selected Topics in Power Electronics, 12/2019, **QORIA Taoufik**, GRUSON François, COLAS Frédéric, DENIS Guillaume, PREVOST Thibault, GUILLAUD Xavier

[2] "*Current Limiting Algorithms and Transient Stability Analysis of Grid-Forming VSCs"* Electric Power Systems Research (EPSR), **QORIA Taoufik**, GRUSON François, COLAS Frédéric, GUILLAUD Xavier

[3] "*Classification of Droop-Based Grid-Forming Control Schemes: Application in Forced Commutated Converter-Based HVDC Systems"* Electric Power Systems Research (EPSR), ROKROK Ebrahim, **QORIA Taoufik**, BRUYERE Antoine, FRANCOIS Bruno, GUILLAUD Xavier

[4] "*Direct AC Voltage Control for Grid-forming Inverters"* Journal of Power Electronics, **QORIA Taoufik**, LI Chuanyue Li, OUE Ko, GRUSON François, COLAS Frédéric, GUILLAUD Xavier

[5] "*Coupling influence on the dq impedance stability analysis for the three-phase grid-connected inverter"* MDPI Energies, 09/2019, LI Chuanyue Li, **QORIA Taoufik**, COLAS Frédéric, JUN Liang, WENLONG Ming, GRUSON François, GUILLAUD Xavier

[6] "*A PLL-free grid-forming control with decoupled functionalities for high-power applications"* IEEE Access, **QORIA Taoufik**, ROKROK Ebrahim, BRUYERE Antoine, FRANCOIS Bruno, GUILLAUD Xavier

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[13] "*Tuning of AC voltage-controlled VSC based Linear Quadratic Regulation"* IEEE PowerTech19, 06/2019 **QORIA Taoufik**, LI Chuanyue Li, OUE Ko, GRUSON François, COLAS Frédéric, GUILLAUD Xavier, PREVOST Thibault

[14] "*Inertia effect and load sharing capability of grid-forming converters connected to a transmission grid"* 15th ACDC19, 02/2019 **QORIA Taoufik**, GRUSON François, COLAS Frédéric, DENIS Guillaume, PREVOST Thibault, GUILLAUD Xavier

[15] "*Tuning of cascaded controllers for robust grid-forming Voltage Source Converter"* Power Systems Computation Conference, 06/2018 QORIA **Taoufik**, GRUSON François, COLAS Frédéric, GUILLAUD Xavier

[16] "*Development of a power hardware in the loop simulation of an islanded Microgrid"* IECON'19, 10/2019 FAKHAM Hicham, **QORIA Taoufik**, LEGRY Martin, DUCARME Olivier, COLAS Frédéric

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Grid forming Converters connected to the Transmission System

From general considerations to practical applications

PowerTech
MADRID 2021
POWER FOR THE SUSTAINABLE DEVELOPMENT GOALS

Thank you for your attention