Fundamental considerations about the control of power electronic converters connected to the transmission grid

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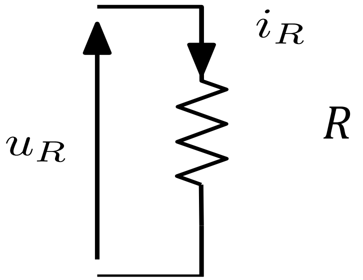
The power electric system is facing a huge challenge with the increase of power electronic converters in the transmission system. In fact, the challenges are many fold.

On this challenge is the question of the definition and characterization of the devices which are connected to the grid

With a simple system : the things are clear

Example of a resistance

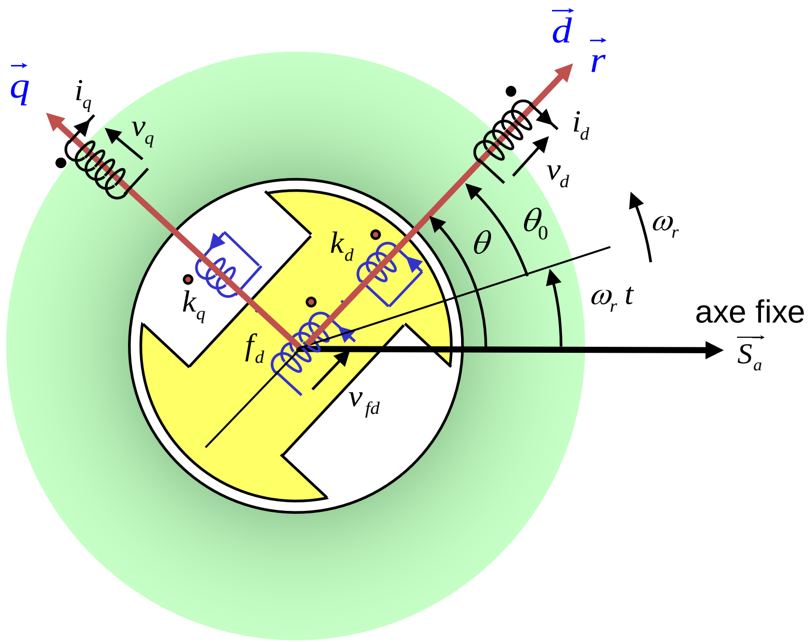


$$u_R = R\, i_R$$

There is no debate, the equation is accepted by every body.

It is quite easy to characterize this device.

With a the synchronous machines, the things become less easy



$$v_d = -R_a\, i_d + \frac{d\psi_d}{dt} - \psi_q\, \omega_r$$

$$v_q = -R_a\, i_q + \frac{d\psi_q}{dt} + \psi_d\, \omega_r$$

$$v_{fd} = R_{fd}\, i_{fd} + \frac{d\psi_{fd}}{dt}$$

$$0 = R_{kd}\, i_{kd} + \frac{d\psi_{kd}}{dt}$$

$$0 = R_{kq}\, i_{kq} + \frac{d\psi_{kq}}{dt}$$

$$\psi_d = -L_{aad}\, i_d + L_{afd}\, i_{fd} + L_{akd}\, i_{kd}$$

$$\psi_q = -L_{aaq}\, i_q + L_{akq}\, i_{kq}$$

$$\cdots$$

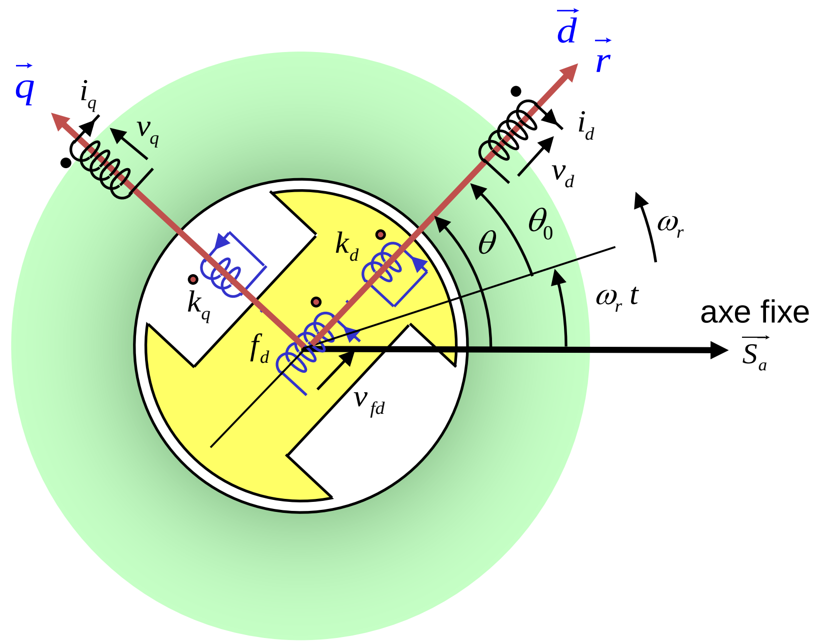
Not that easy to characterize all the elements

More over, there is a control which is applied to this machine

There are some standard IEEE controls DC, AC, SS …

But it is known that a lot of industrial controls are different from this standard control.

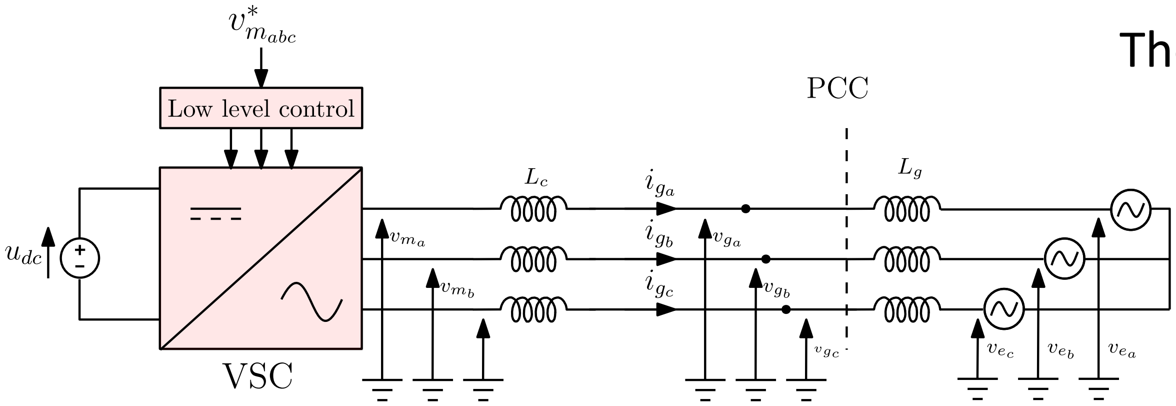
With a the synchronous machines, the things become less easy



The generic dynamic behaviour of the synchronous machine it self is well known

The control can modify it (e.g. PSS) but it doesn't change the overall behavior since the inherent electromechanical behaviour has still a very strong influence on the final dynamic behaviour

With the power electronic converters, the things are coming even much more difficult



The aim of the low level control is to obtain:

$$\langle v_{ma} \rangle_{T_s} \approx v^*_{ma}$$

$$\langle v_{m_b} \rangle_{T_s} \approx v^*_{ma}$$

$$\langle v_{m_c} \rangle_{T_s} \approx v^*_{ma}$$

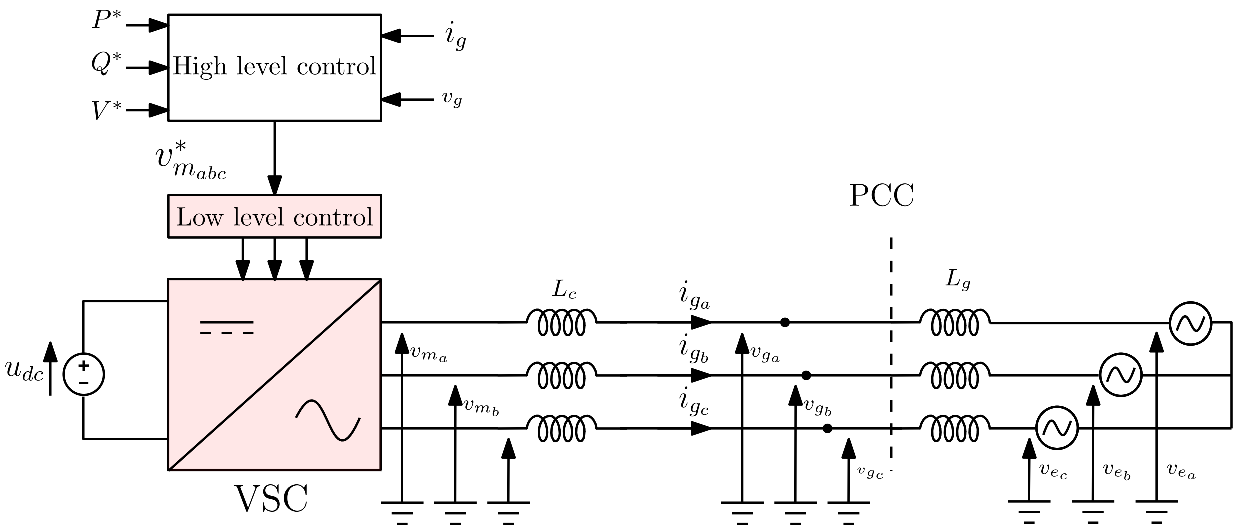
T_e: switching period

If so, the power electronic converter converter can be considered as a perfect gain.

Its own internal dynamic can be neglected.

This is not 100% true but it gives the general trend.

The dynamics of the system mainly depends on the high level converter. An in the real life, this block is nearly a black box



For the transmission system application, TSOs are writing grid codes. But there are not allowed to impose any specific control, they can only specify some requirements.

This has been done in the 1st version of 'RfG' grid code but the 2nd version of the grid code will have to include the complex question of grid forming

Entsoe + other stakeholders have published a document with a list of functionnalities for the grid forming

Creates system voltage (does not rely on being provided with firm clean voltage)

- Contributes to Fault Level (PPS & NPS within first cycle)
- Contributes to TSI (limited by energy storage capacity)
- Supports system survival to allow effective operation of LFDD for rare system splits.
- Controls act to prevent adverse control system interactions
- Acts as a sink to counter harmonics & inter-harmonics in system voltage
- Acts as a sink to counter unbalance in system voltage

Germany

FNN Guideline: Grid forming behaviour of HVDC systems and DC-connected PPMs

Supplement to VDE-AR-N 4131 for dynamic frequency/active power behaviour and dynamic voltage control without reactive current specification

UK

GC0137: Minimum Specification Required for Provision of GB Grid Forming (GBGF) Capability (formerly Virtual Synchronous Machine/VSM Capability)

MIGRATE

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OPTIMAL SYSTEM-MIX OF FLEXIBILITY SOLUTIONS FOR EUROPEAN ELECTRICITY

Grid-Forming Inverters: Are They the Key for High Renewable Penetration?
IEEE Power Magazine 2019 J. Matevosyan; B. Badrzadeh; T. Prevost; ....

...

Uncountless different specifications of grid forming

None of them are a real precise definition

One common characteristics : A voltage source behind an inductance

In standalone situation : this definition can be considered as sufficient.

In grid connected : the voltage source has to be driven.

Proposal for a definition of grid connected - grid forming

A grid connected grid forming principle is based on the control of the active power with a voltage angle.

From this definition, it is possible to derive the fundamental grid forming control

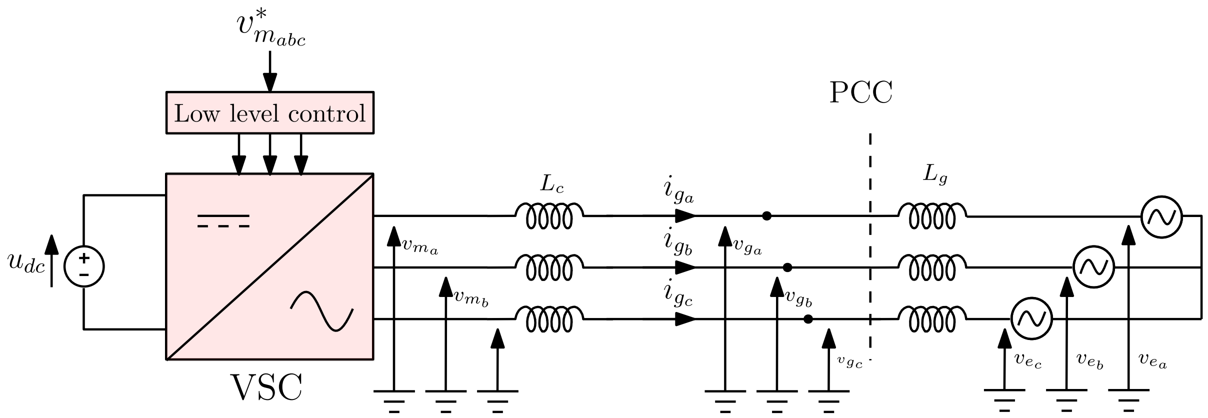
Outline of the presentation

1 – Presentation of 2 main controls deduced from this fundamental definition

2 – Application to MMC based HVDC link

3 - Conclusion

Let’s start from a simplified representation of a VSC



As said before, we consider that

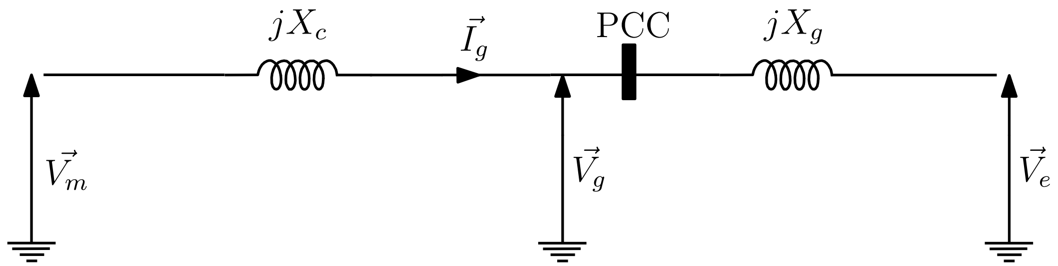
$$\langle v_{ma} \rangle_{T_s} \approx v^*_{ma}$$

$$\langle v_{m_b} \rangle_{T_s} \approx v^*_{ma}$$

$$\langle v_{m_c} \rangle_{T_s} \approx v^*_{ma}$$

This VSC is a « driven voltage source »

Let’s represent this system by a single phase steady state modeling

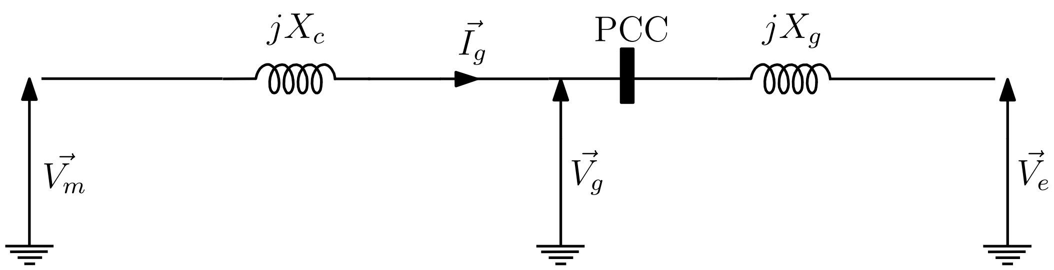


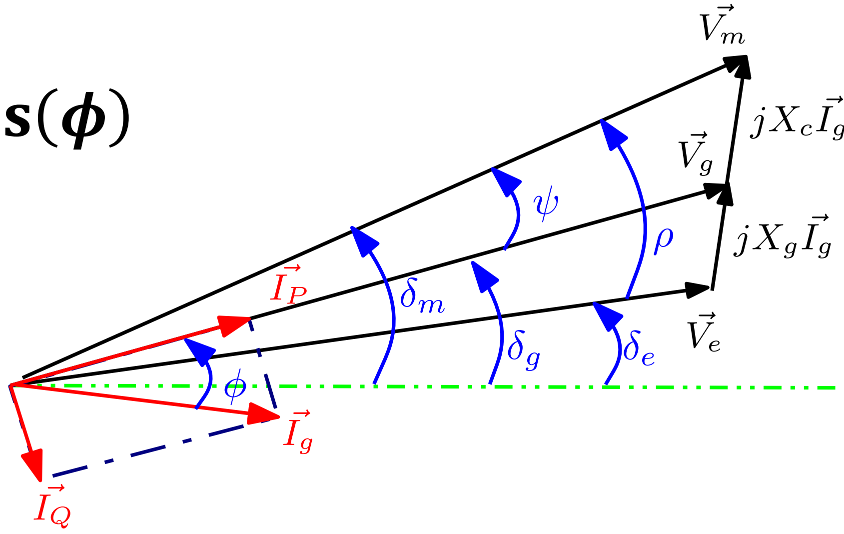
$\bar{V}_m = V_m \, e^{j\delta_m}$ $\bar{V}_g = V_g \, e^{j\delta_g}$ $\bar{V}_e = V_e \, e^{j\delta_e}$

From this single phase phasor modeling of the system, it can be derived three different formula for the active power

$$\bar{I}_g = I_g\, e^{-j\phi}$$

$$P = V_g I_g \cos(\phi)$$





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

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

$$P = \frac{V_m V_e}{X_c + X_g} \sin(\delta_m - \delta_e)$$

The converter can control the angle δ_m.

From this formula, it can be deduced that the active power can be controlled thanks to the difference between δ_m and δ_g or δ_m and δ_e

$$P = V_g I_g \cos(\phi)$$

The control of the active power supposes to drive **the current I_g** in phase and magnitude. A current loop and an information on the grid voltage angle is needed.

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

The control of the active power is directly linked with the modulated voltage angle difference of angle between δ_m and δ_g An information on the grid voltage angle is needed

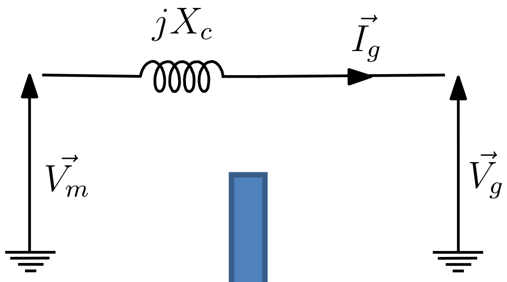
$$P = \frac{V_m V_e}{X_c + Xg} sin(\delta_m - \delta_e)$$

The control of the active power is directly linked with the modulated voltage angle difference of angle between δ_m

First solution for the control :

Use of an estimate of the voltage angle at PCC

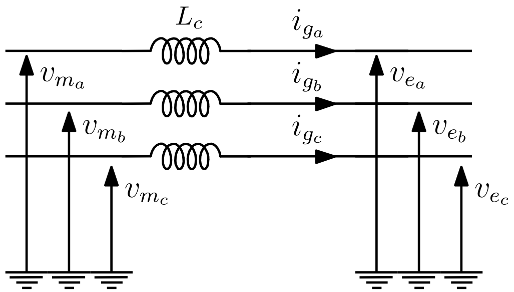
Phasor quasi static model



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

Phasor angles

Dynamic EMT model



$$v_{ma}(t) = V_m\sqrt{2}\sin(\omega_b t + \delta_m) = V_m\sqrt{2}\sin(\theta_m)$$

$$v_{mb}(t) = V_m\sqrt{2}\sin(\omega_b t - 2\pi/3 + \delta_m) = V_m\sqrt{2}\sin(\theta_m - 2\pi/3)$$

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

$$v_{ga}(t) = V_e\sqrt{2}\sin(\omega_b t + \delta_m) = V_g\sqrt{2}\sin(\theta_g)$$

$$v_{eb}(t) = V_e\sqrt{2}\sin(\omega_g t + \delta_m - 2\pi/3) = V_g\sqrt{2}\sin(\theta_g - 2\pi/3)$$

$$v_{ec}(t) = V_e\sqrt{2}\sin(\omega_g t + \delta_m - 4\pi/3) = V_g\sqrt{2}\sin(\theta_g - 4\pi/3)$$

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

$$v_{ma}(t) = V_m\sqrt{2}\sin(\theta_g + \psi)$$

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

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

$$P = \frac{V_g V_m}{X_c} sin(\theta_m - \theta_g)$$

Time domain angles

The converter controls the instantaneous three-phase modulated voltage $v_{m_{abc}}$ in magnitude V_m and angle θ_m

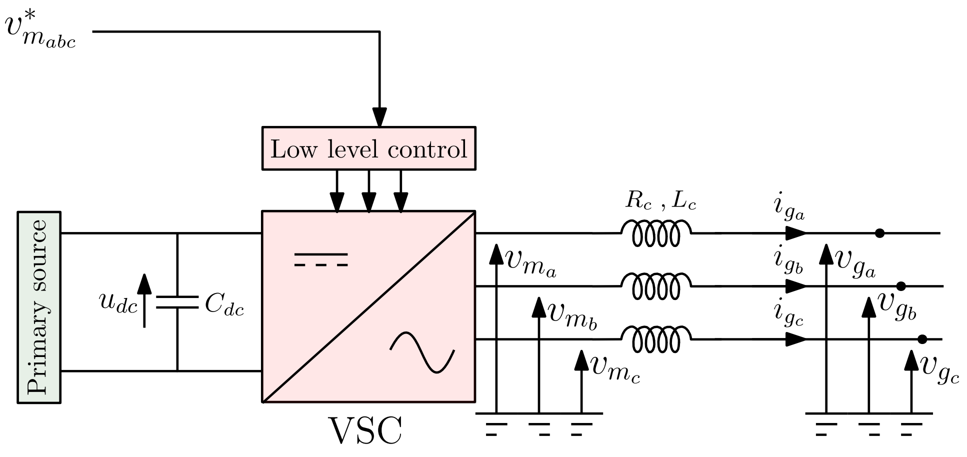
$$P = \frac{V_g V_m}{X_c} sin(\theta_m - \theta_g) = \frac{V_g V_m}{X_c} sin(\psi)$$

In order to control P, an information on θ_g is needed

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

$$v_{mb}^*(t) = V_m\sqrt{2}\sin(\theta_m - 2\pi/3)$$

$$v_{mc}^*(t) = V_m\sqrt{2}\sin(\theta_m - 4\pi/3)$$



$$v_{ga}(t) = V_e\sqrt{2}\sin(\omega_b t + \delta_m) = V_g\sqrt{2}\sin(\theta_g)$$

$$v_{eb}(t) = V_e\sqrt{2}\sin(\omega_g t + \delta_m - 2\pi/3) = V_g\sqrt{2}\sin(\theta_g - 2\pi/3)$$

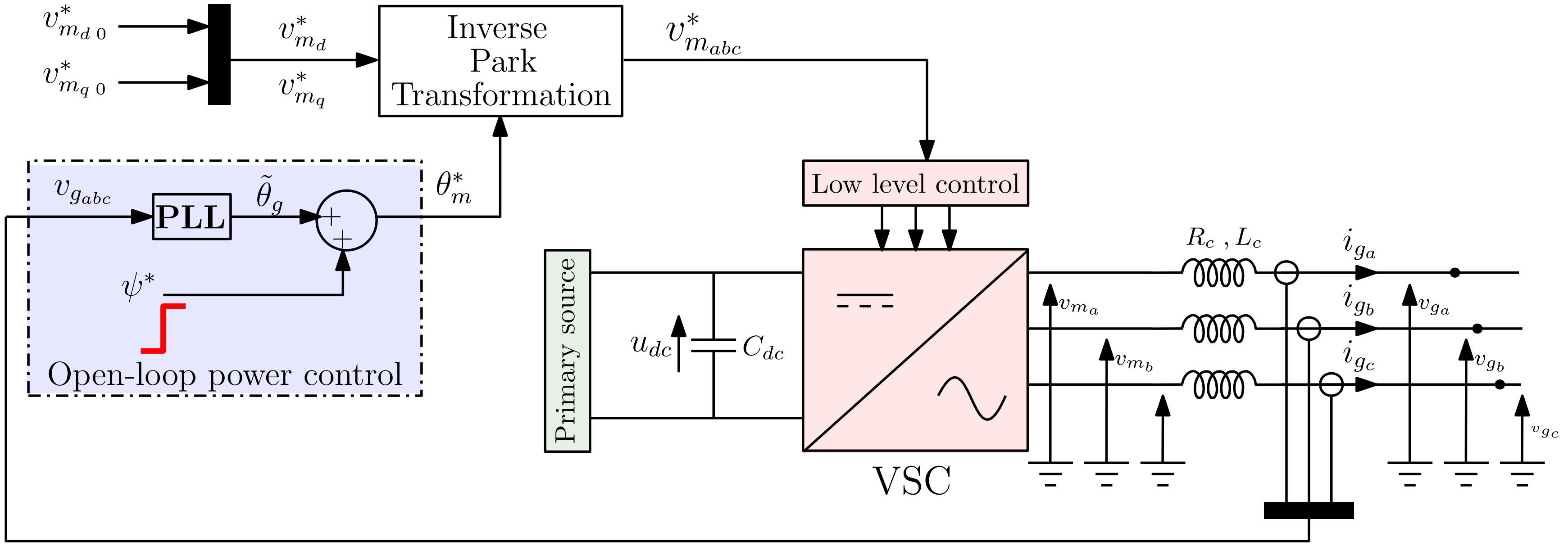
$$v_{ec}(t) = V_e\sqrt{2}\sin(\omega_g t + \delta_m - 4\pi/3) = V_g\sqrt{2}\sin(\theta_g - 4\pi/3)$$

The control can be implemented in Park frame

Let's define $\tilde{\theta}_g$ the estimate of θ_g.

Let's define ψ^*, such as $\theta_m = \tilde{\theta}_g + \psi^*$

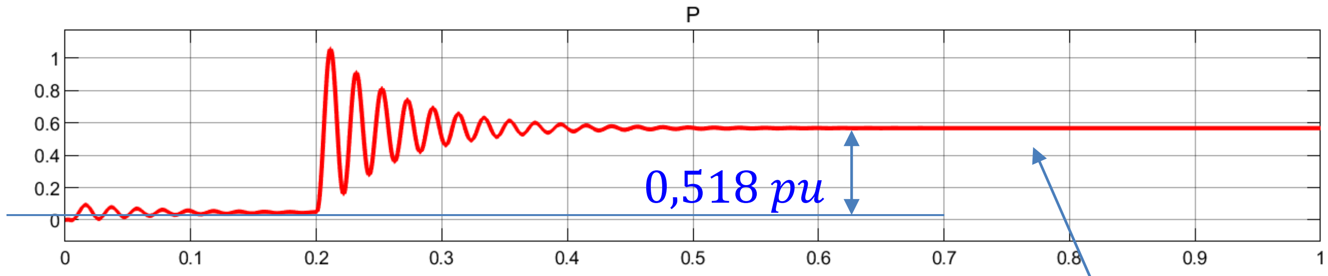
$$v^*_{md0} = V_m$$
$$v^*_{mq0} = 0$$



In steady state $\tilde{\theta}_g = \theta_g$

$$\boldsymbol{P = \frac{V_g V_m}{X_c} \sin(\psi^*)}$$

The steady state model is correct but the poorly damped poles of the system induce an oscillatory behavior for the systems



It can be demonstrated that :

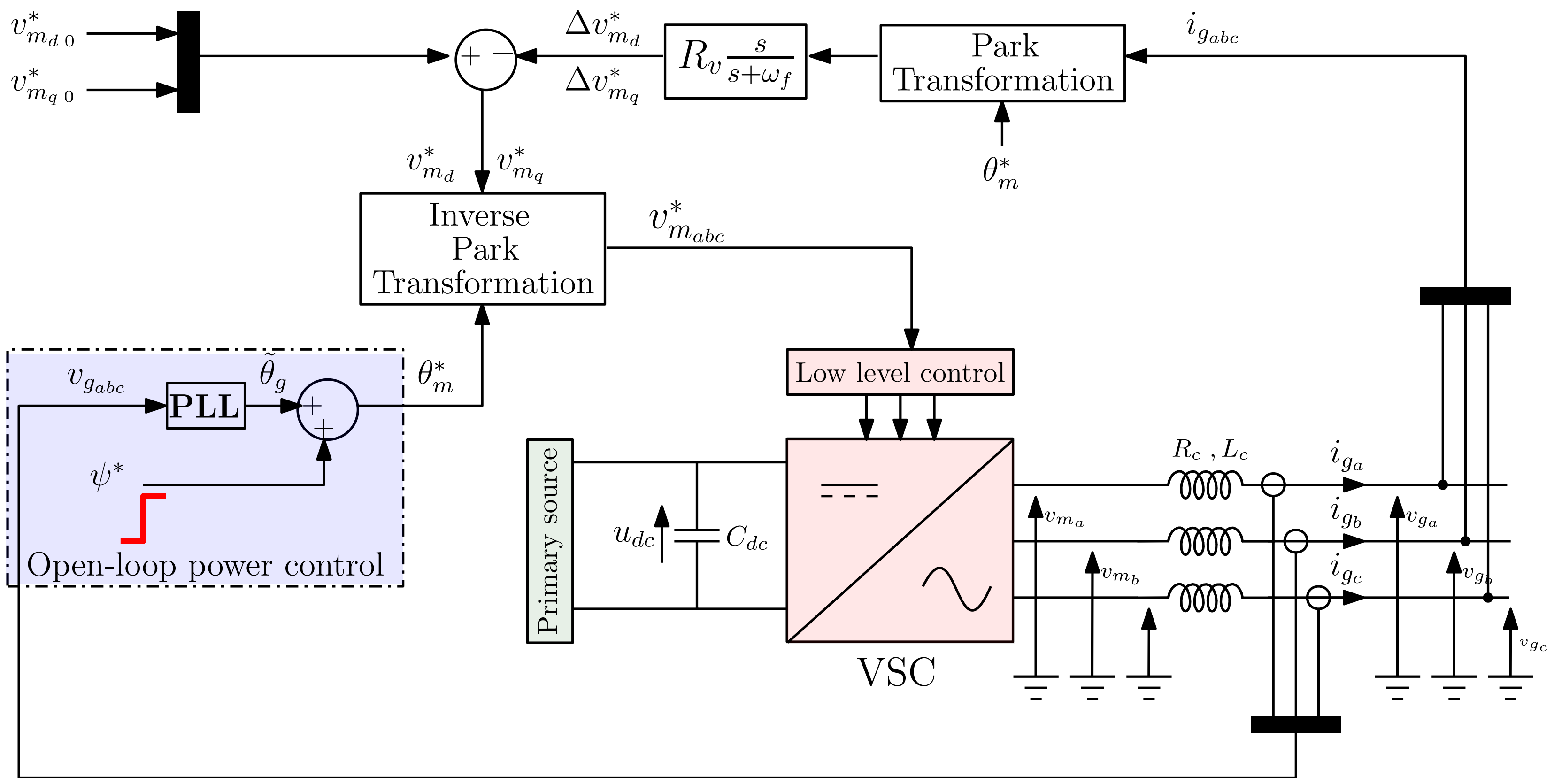
$$\Delta P \approx \frac{V_g V_m}{X_c} \frac{1}{\left(R_c + \frac{L_c}{\omega_b} s\right)^2 + (L_c \omega_b)^2} \Delta\delta_m$$

$$P = \frac{V_g V_m}{X_c} sin(\psi^*)$$

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

1st solution : Power control with an information at the PCC



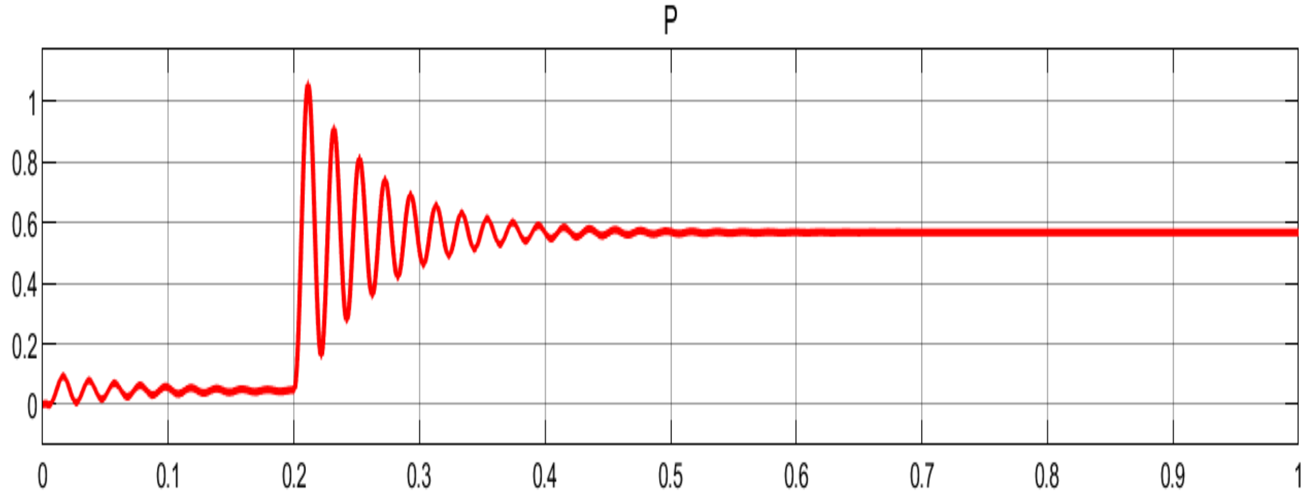
A virtual damping resistance is introduced in the control

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

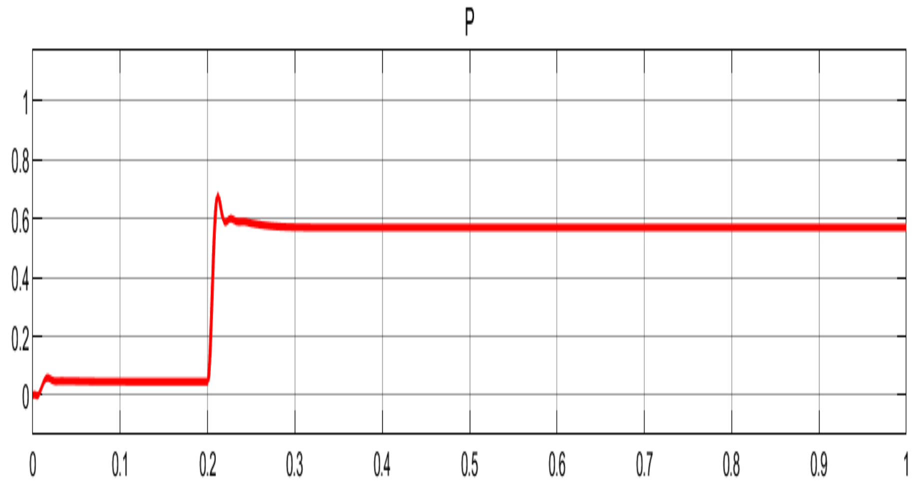
To cancel its effect in steady state, a washout filter is added

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

Without damping resistance



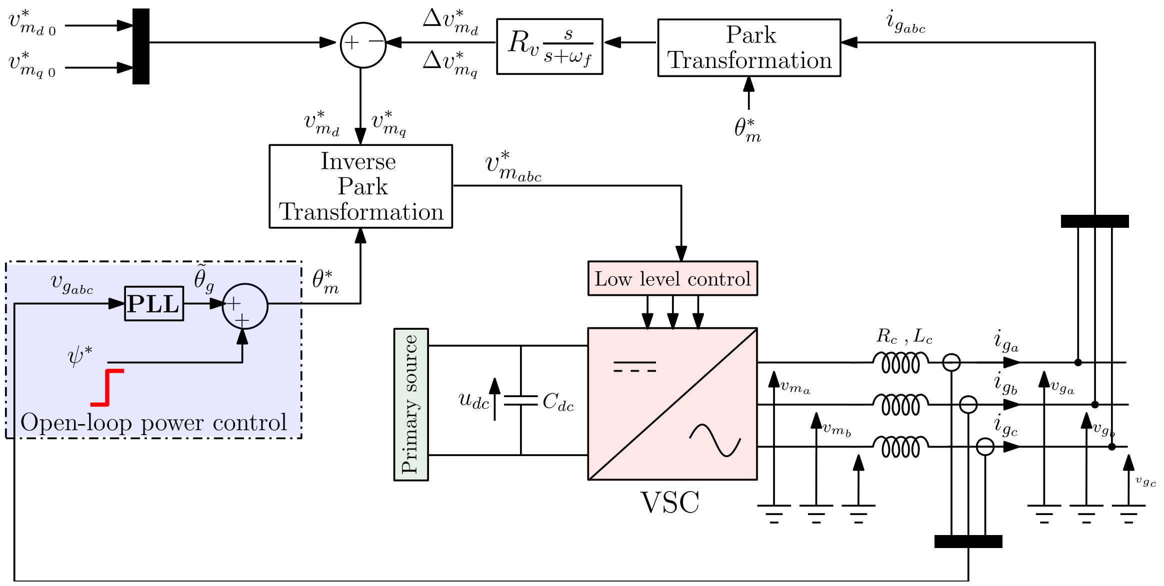
With damping resistance

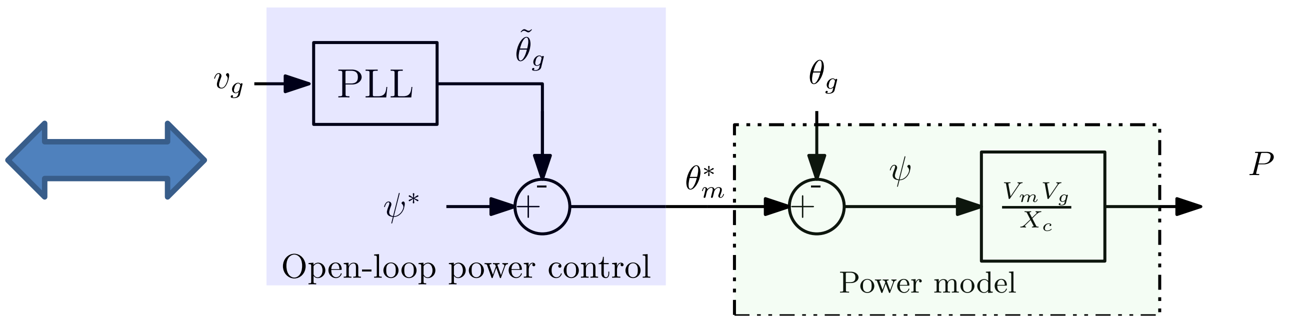


$R_v = 0.09 \quad \omega_f = 60\, rad/s$

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

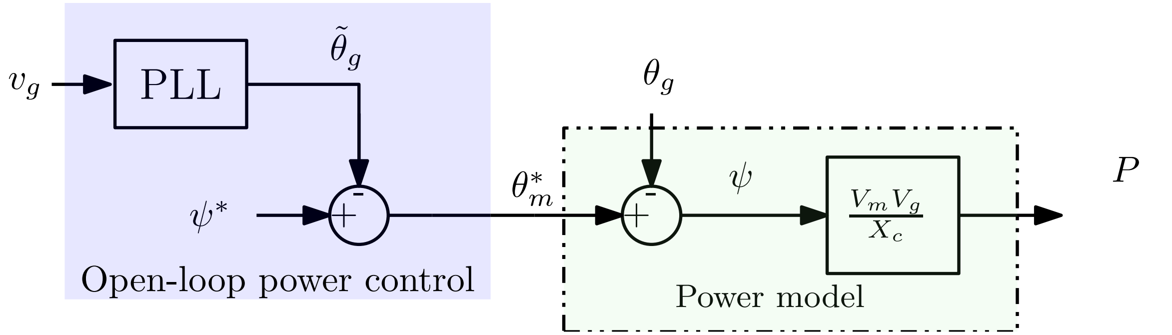
1st solution : Power control with an information at the PCC



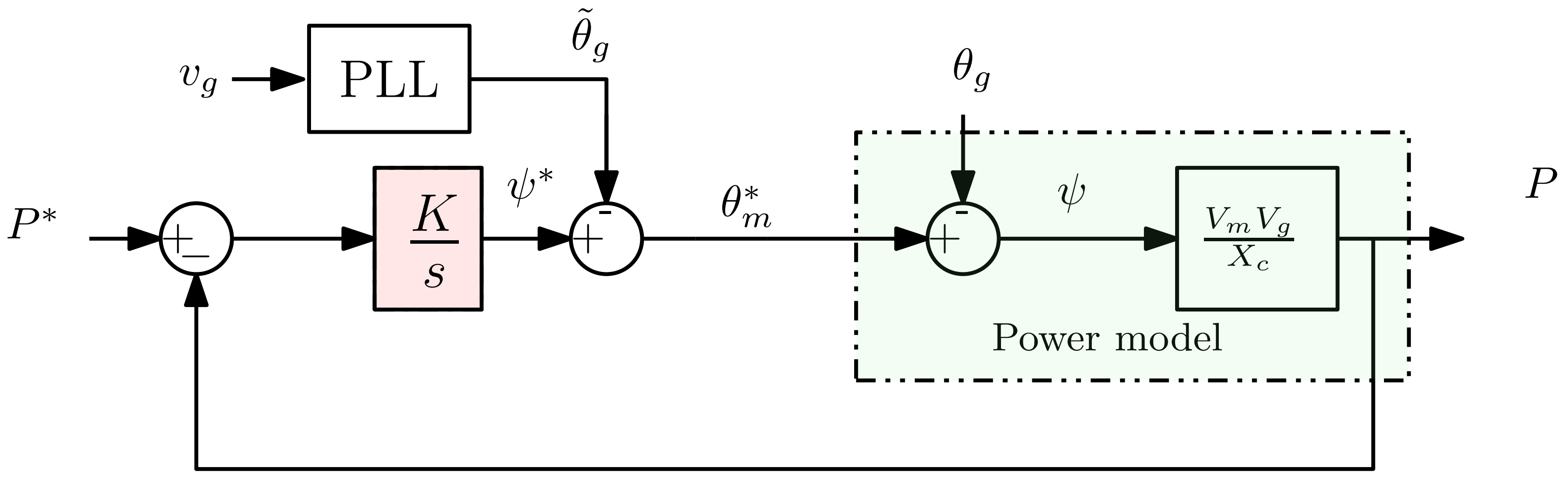


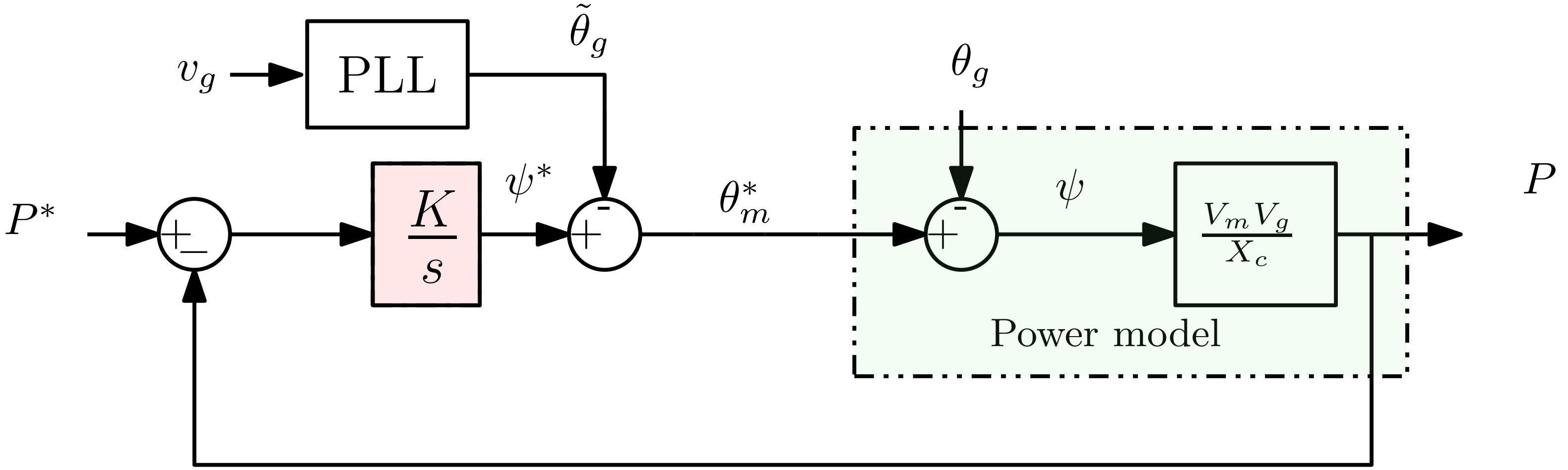
This open loop control would not be reliable enough in practical application. Hence, a closed-loop control is implemented

Open loop control



Closed loop control



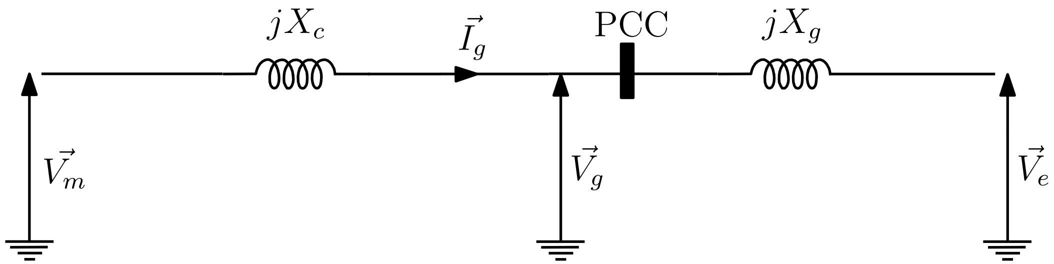


It possible to obtain $P = P^*$ in steady state

K has an in influence on the closed loop dynamics.
The dynamics cannot be choosen too high due to the assumptions which have been done on the model.

This control is robust against grid impedance variation since this impedance has no influence in the simplified model.

In practice, the short circuit ratio may have a slight influence on the active power dynamics



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

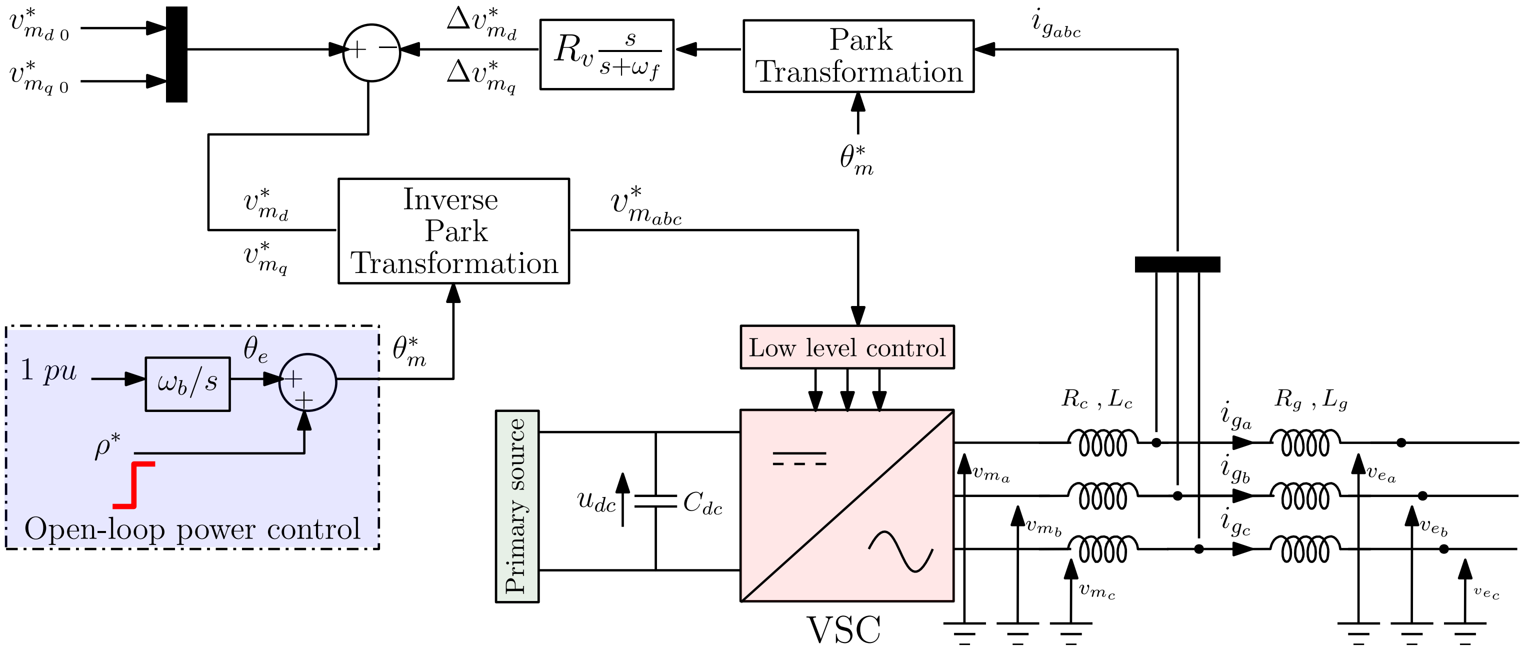
$\bar{V}_e = V_e\, e^{j\delta_e}$

Let’s suppose that no information is available at the PCC.
Let’s suppose that the Thevenin equivalent angle is known.

$$P = \frac{V_m V_e}{X_c + X_g} sin(\delta_m - \delta_e) = \frac{V_m V_e}{X_c + X_g} sin(\rho)$$

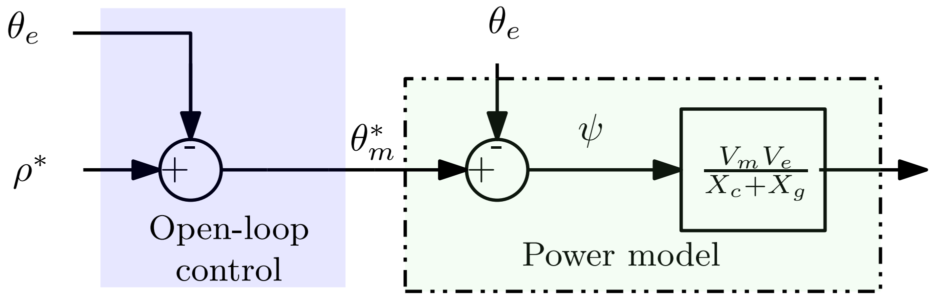
The active power is controlled thanks to the difference of angle between $\bar{V}_m$ and $\bar{V}_e$

The control is implemented in Park frame, a transient virtual impedance is added.

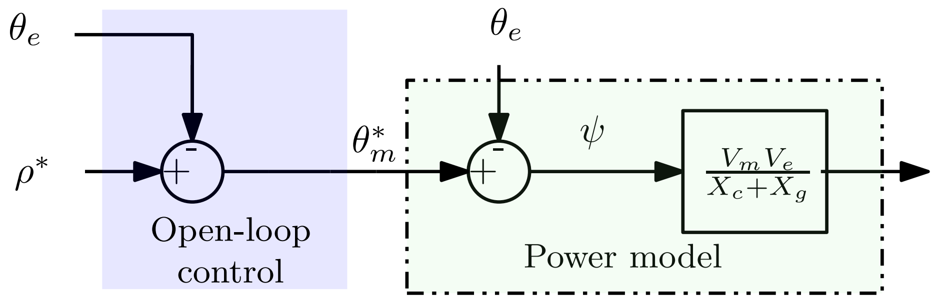


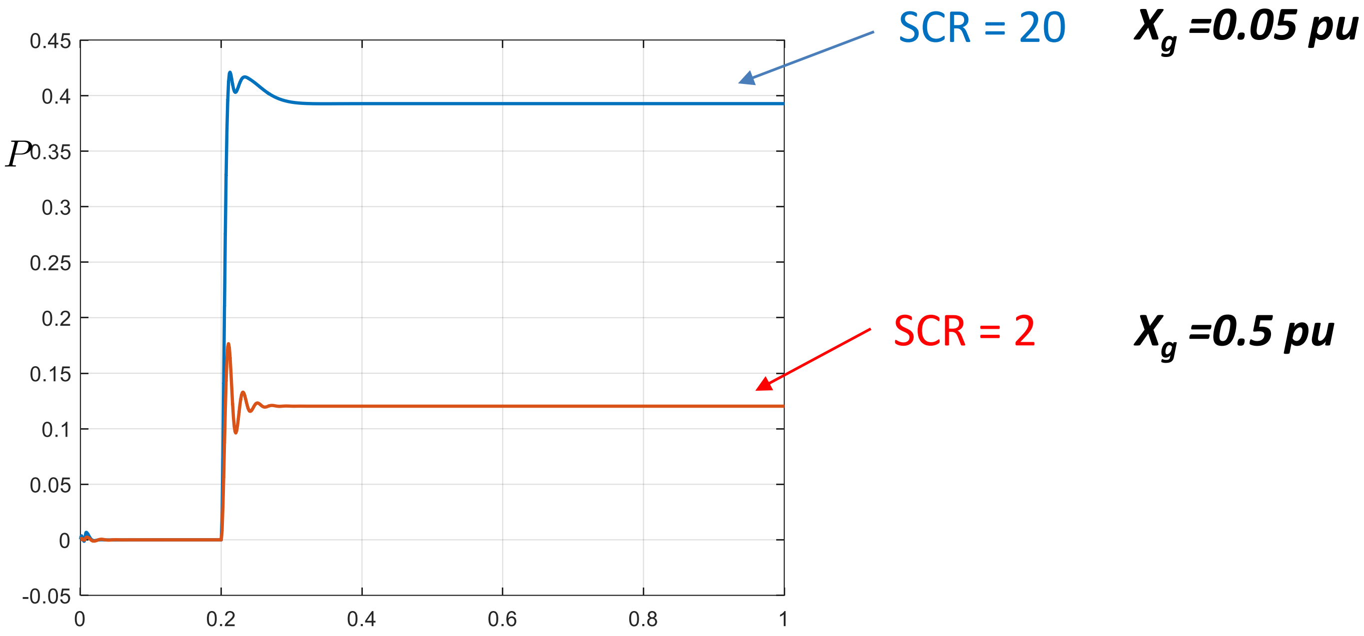
Contrary to the previous model,

The grid impedance X_g is involved in this model



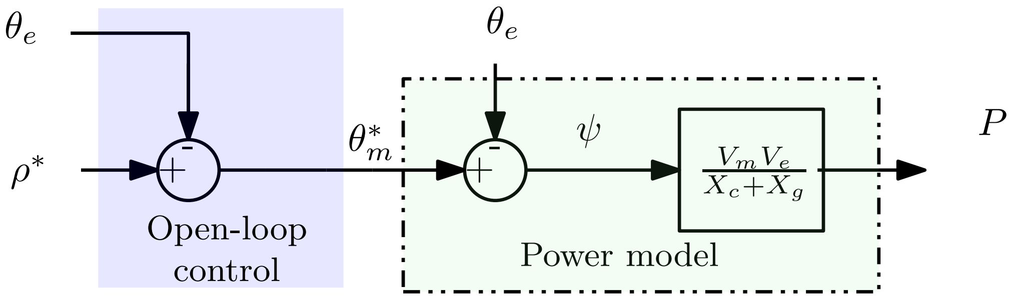
2nd solution : Power control with no information at the PCC



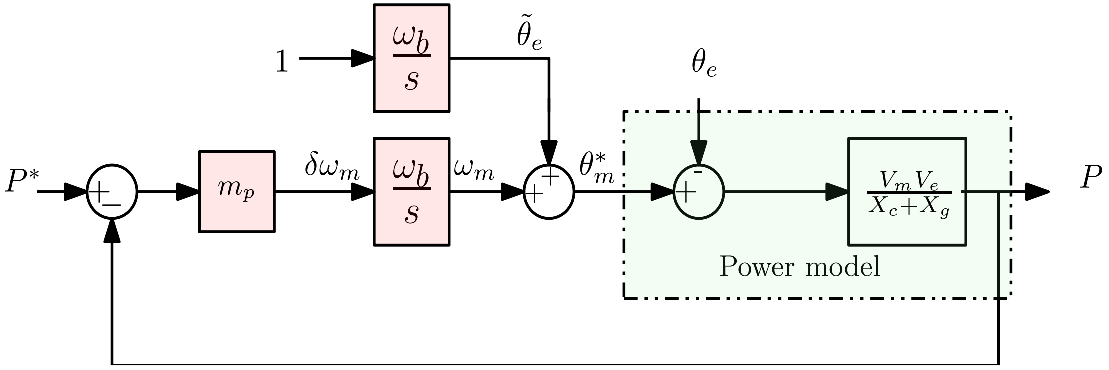


$R_v = 0.1 \quad \omega_f = 60\ rad/s$

As expected, the gain of the model is depending on the SCR



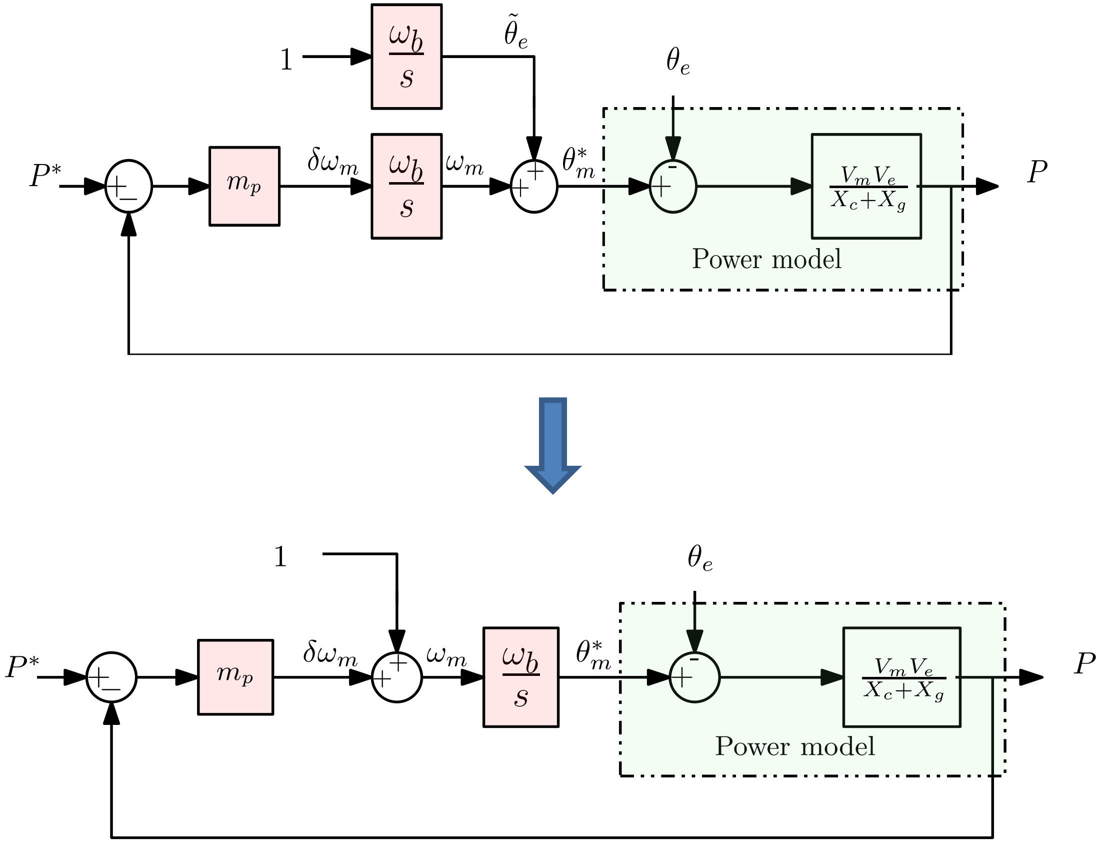
As previously, in practice, this open-loop control would not be reliable enough. A closed-loop system is compulsory



It is not possible to place some sensors on the Thevenin equivalent voltage as previously on the PCC voltage.

A first solution to estimate θ_e is a simple integrator as mentionned on the figure.

2^{nd} solution : Power control with no information at the PCC



This control can be presented in another way.
It highlights ω_m, the frequency of the modulated voltage
In steady state $\omega_m = \omega_g$

Hence, is steady state, it can be written

$$\omega_g = \omega_m = 1 + \mathrm{m_p}(P^* - P)$$

In another way :

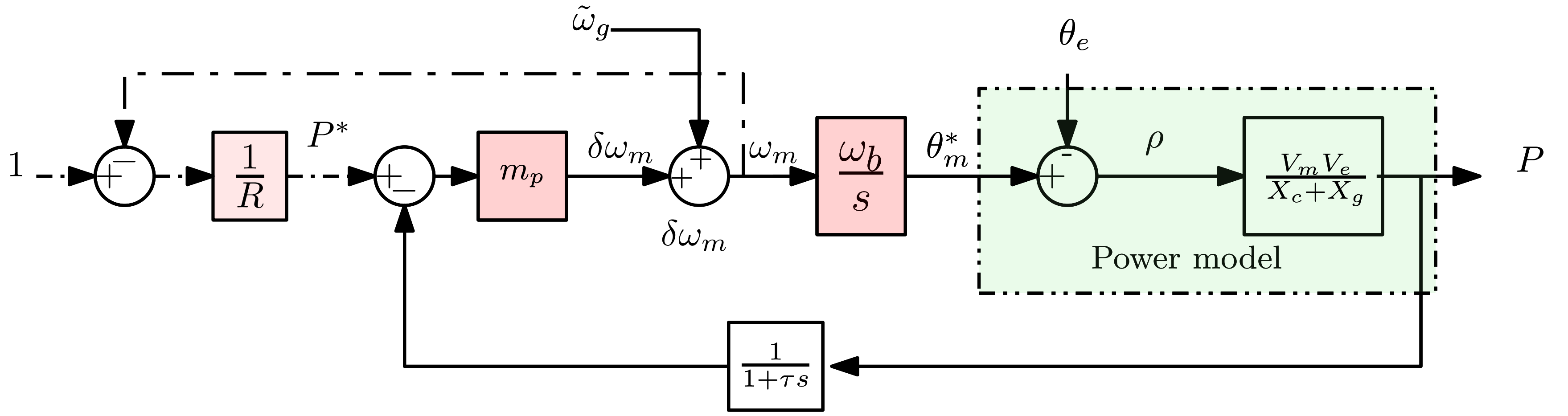
$$P = P^* + 1/\mathrm{m_p}(1 - \omega_g)$$

This clearly a frequency droop equation. m_p is the frequency droop coefficient.

Problem of this type of control : coupling between the frequency droop and the closed loop dynamics.

Two solutions exist to solve this issue.

The first one consists in using an estimate of the grid frequency in the control

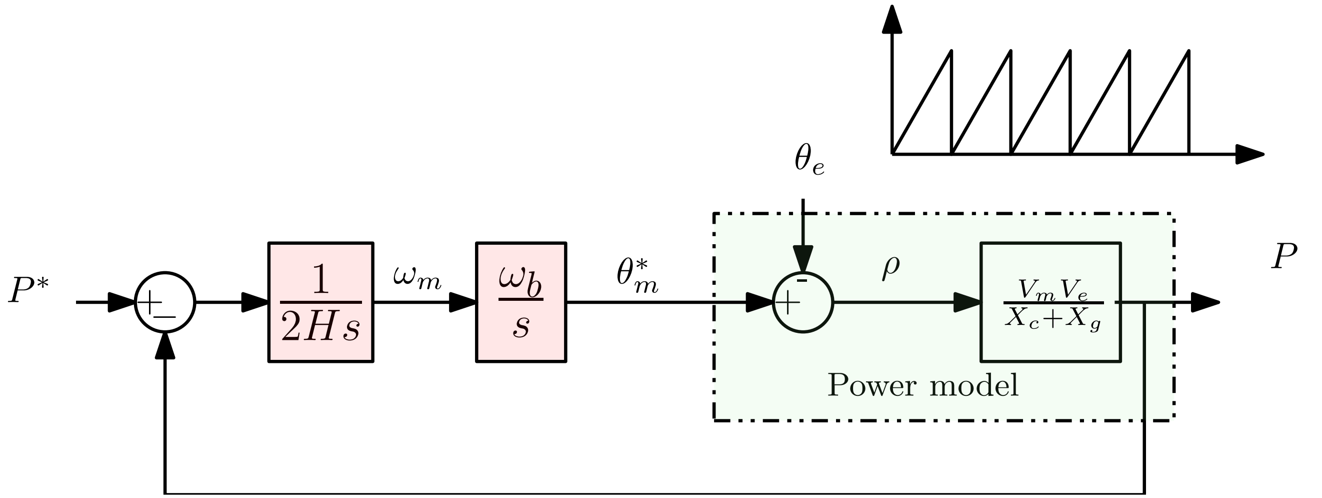


In steady state $\tilde{\omega}_g = \omega_g$, Hence $P = P^*$

m_p gain is calculated with respect to the closed loop dynamics

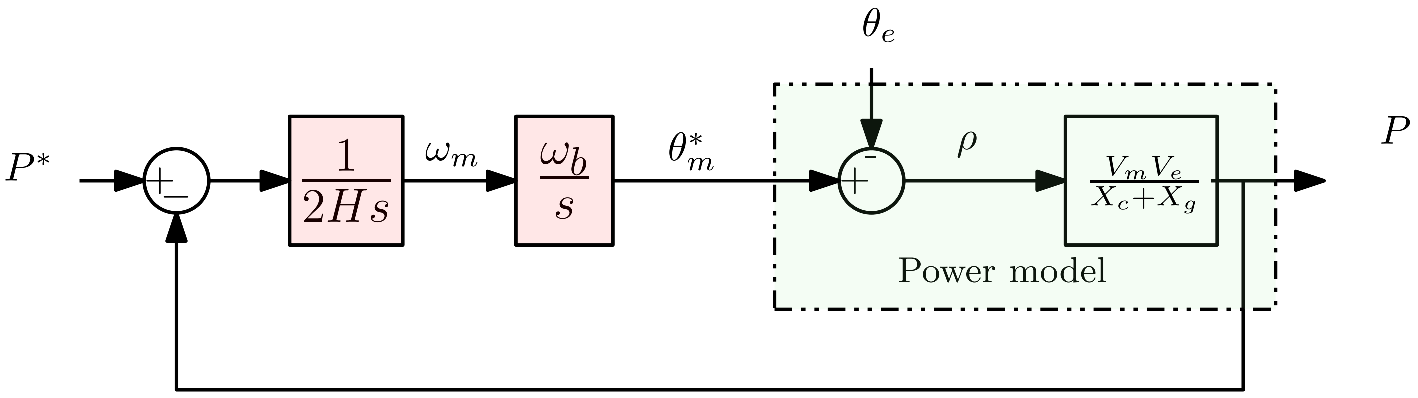
If required, it is possible to add an external frequency droop with a dedicated droop coefficient 1/R

The second one consists in adding a second integrator in the loop.
In steady state ω_m is constant and equals to ω_g
Hence the input of $\frac{1}{2Hs}$ = 0 $\quad P = P^*$



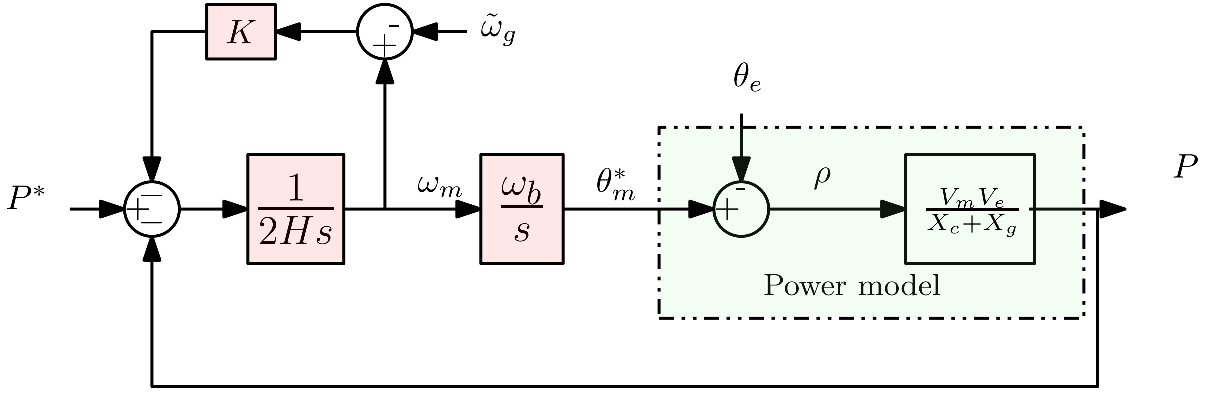
Doing so, an inertial effect is embedded since it can be written $P^* - P = 2H\ d\omega_m/dt$

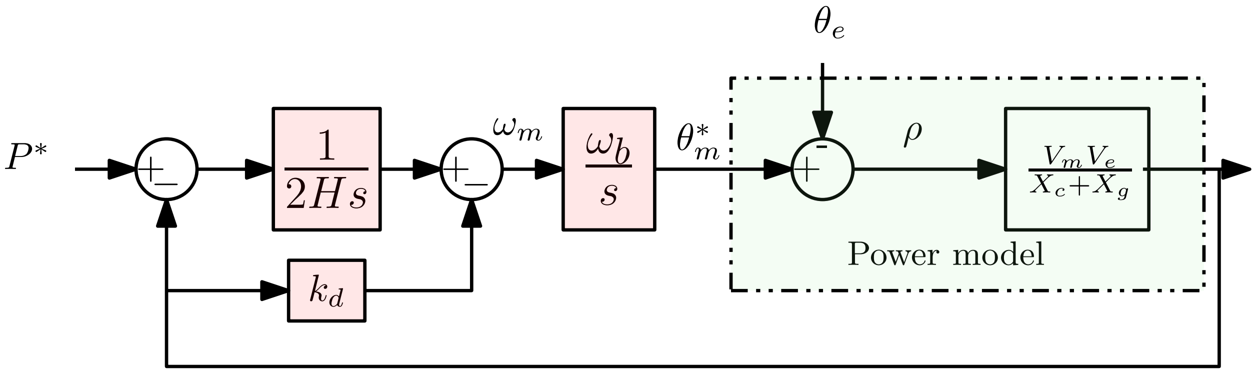
Which is the same type of equation as the « swing equation » in the synchronous machine



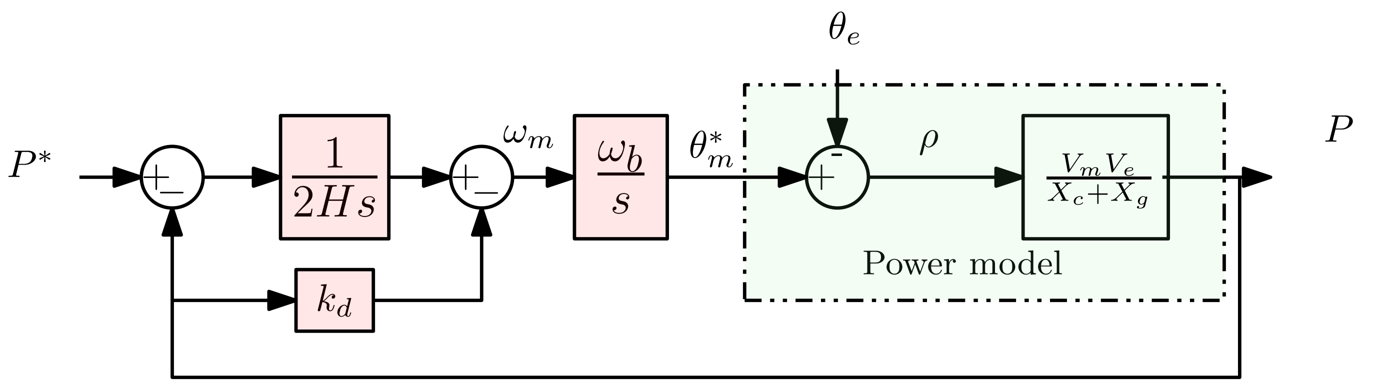
This a second order system with a **null damping.**

A damping effect has to added





Two **possible solution** is the Virtual Synchronous Machine Scheme (VSM)



With the second solution, it is very easy to have a rigourous design of the controller

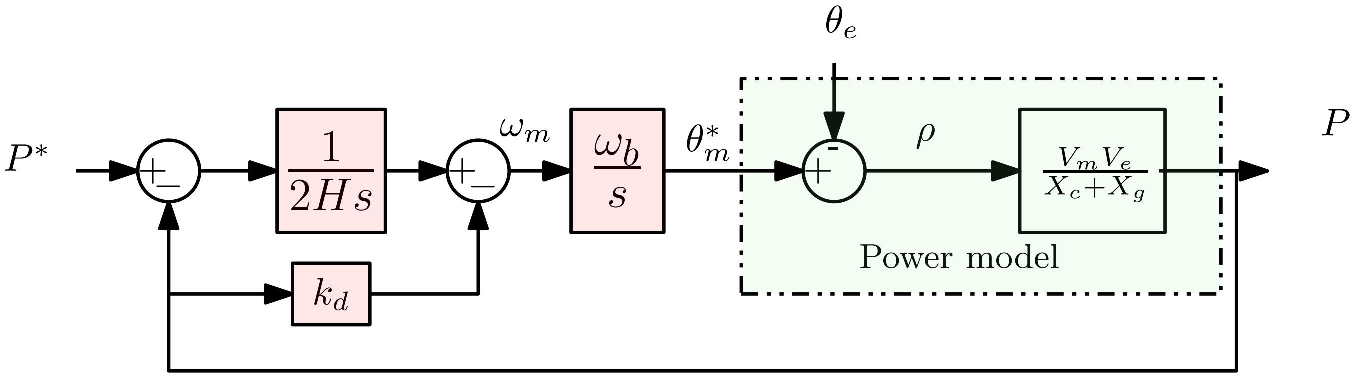
This is a 2nd order system – 2 parameters : natural frequency ω_n, damping ζ

H is choosen by an external consideration (need of an inertial effect on the grid)

k_d is the only degree of freedom of this control

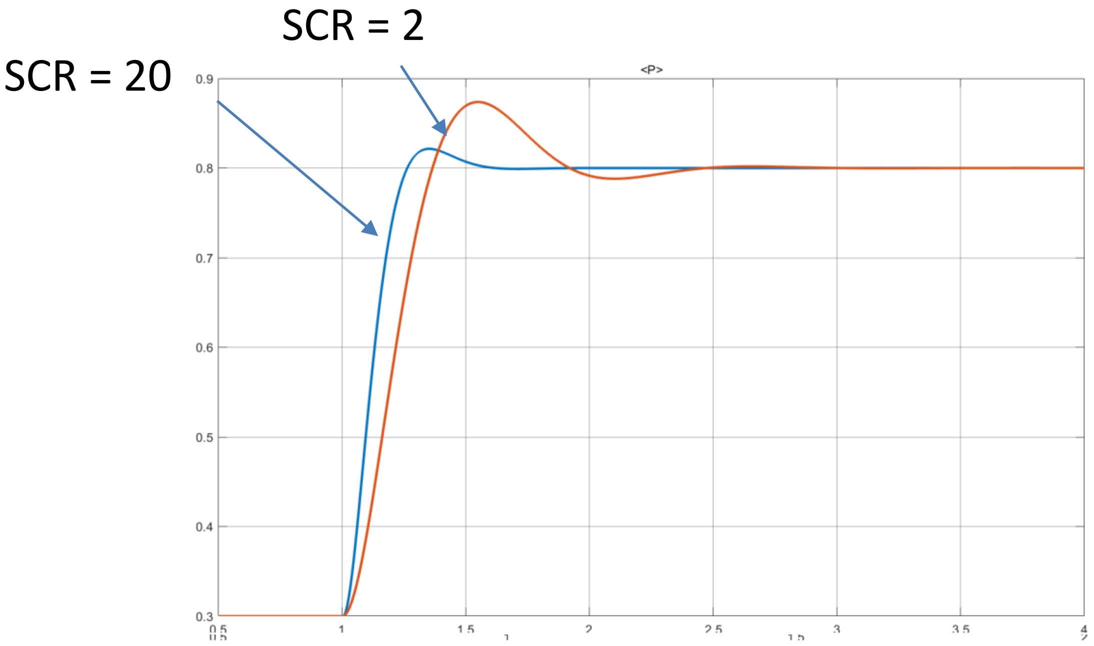
The choice is to control ζ

ω_n is a consequence, **Hence the response time cannot be choosen**

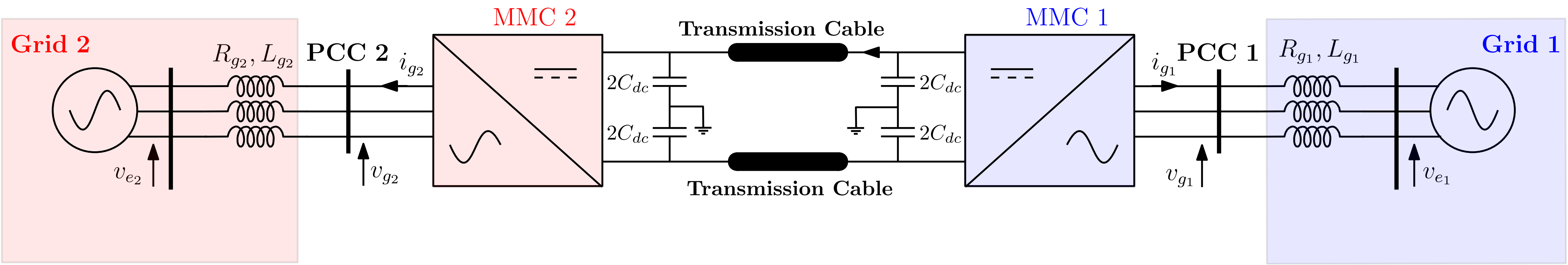


The response time depends on

H and the grid impedance X_g



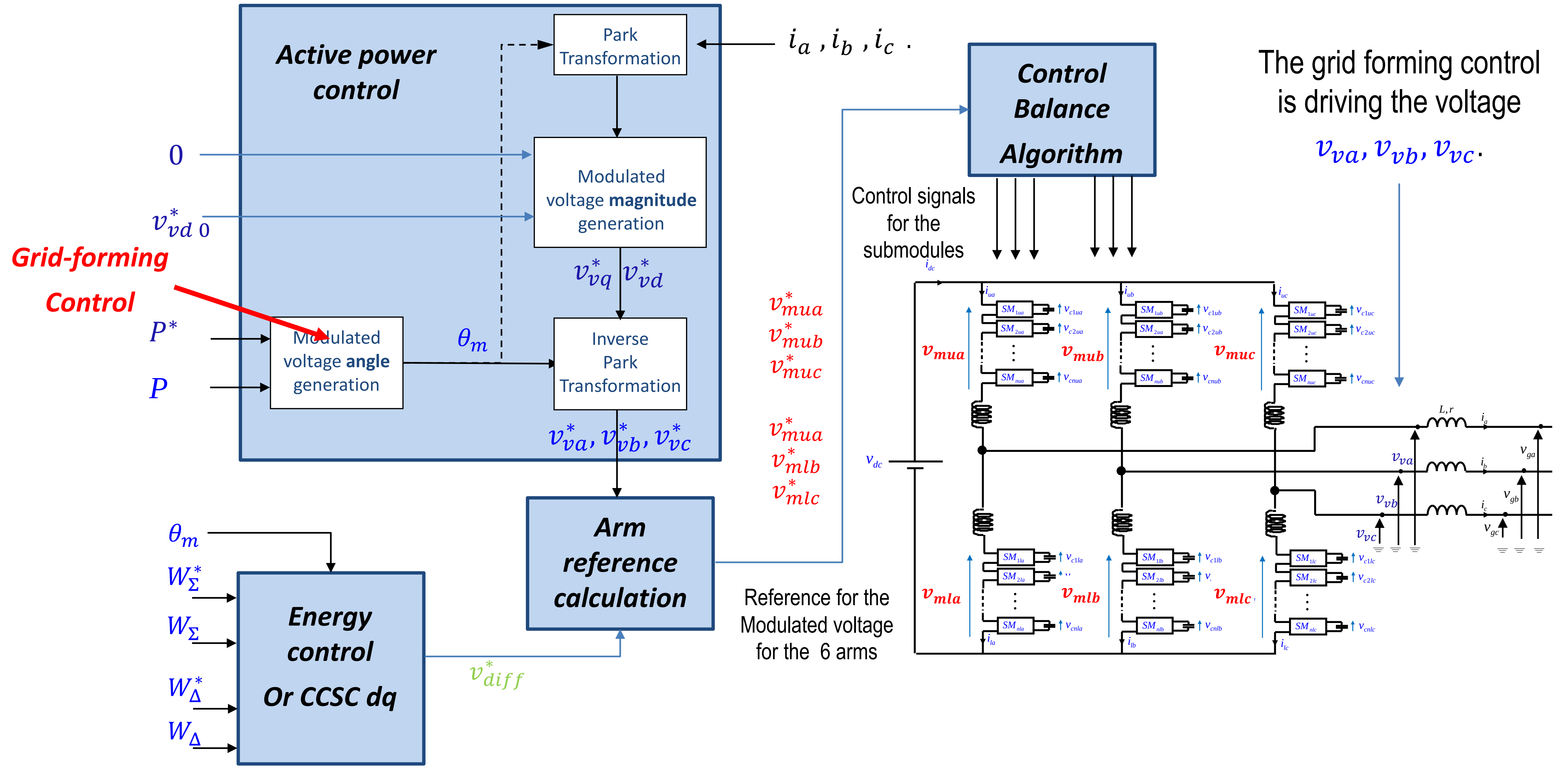
2 – Application to a MMC HVDC

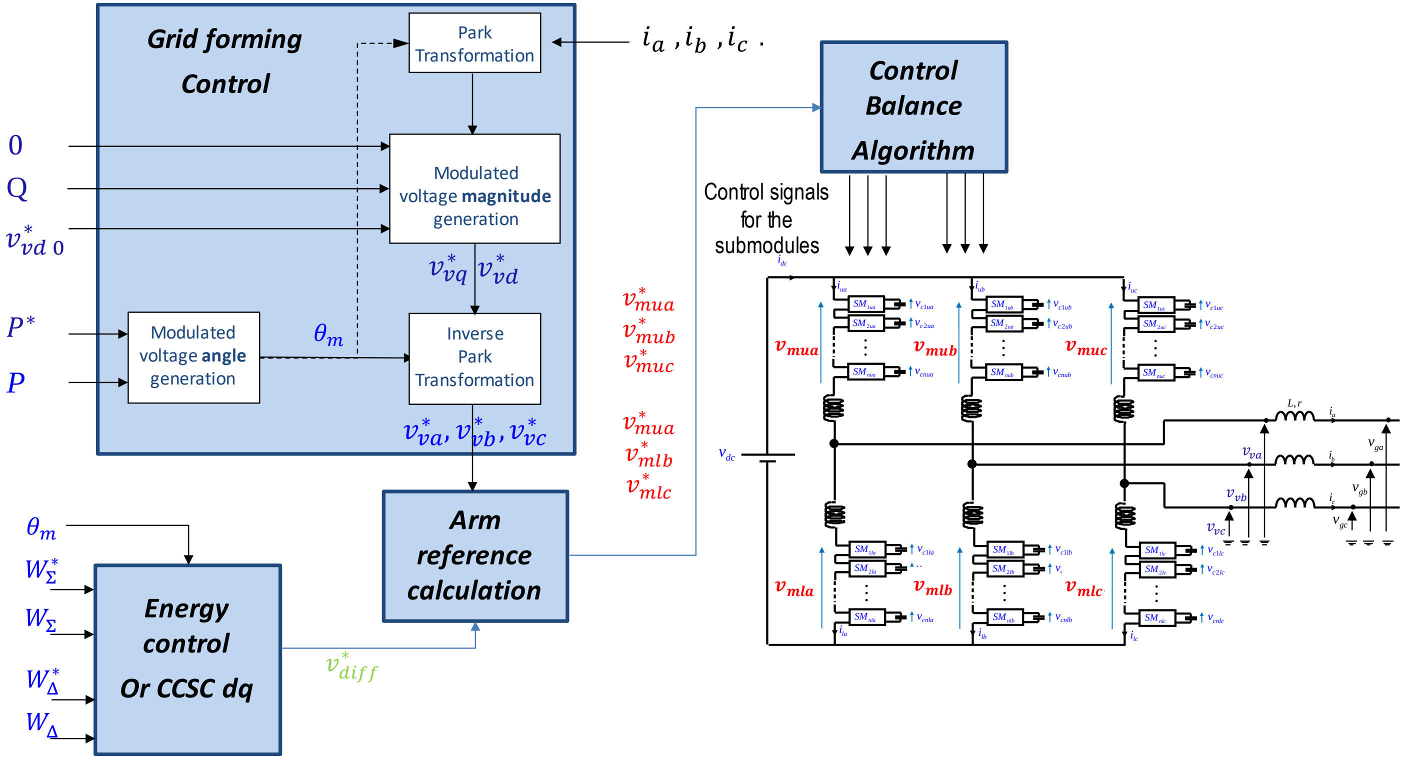


1 – Grid forming and MMC

2 – Grid forming and DC bus control

3 – Grid forming and HVDC


Active power control
Park Transformation
i_a , i_b , i_c .
0
$v^*_{vd\,0}$
Modulated voltage magnitude generation
v^*_{vq} v^*_{vd}
Grid-forming Control
P^*
P
Modulated voltage angle generation
θ_m
Inverse Park Transformation
$v^*_{va}, v^*_{vb}, v^*_{vc}$
Arm reference calculation
θ_m
W^*_Σ
W_Σ
W^*_Δ
W_Δ
Energy control
Or CCSC dq
v^*_{diff}
v^*_{mua}
v^*_{mub}
v^*_{muc}
v^*_{mua}
v^*_{mlb}
v^*_{mlc}
Control Balance Algorithm
Control signals for the submodules
Reference for the Modulated voltage for the 6 arms
v_{mua}
v_{mub}
v_{muc}
v_{mla}
v_{mlb}
v_{mlc}
v_{dc}
i_{dc}
L,r
i_a
i_b
i_c
v_{va}
v_{vb}
v_{vc}
v_{ga}
v_{gb}
v_{gc}
The grid forming control is driving the voltage
v_{va}, v_{vb}, v_{vc}.



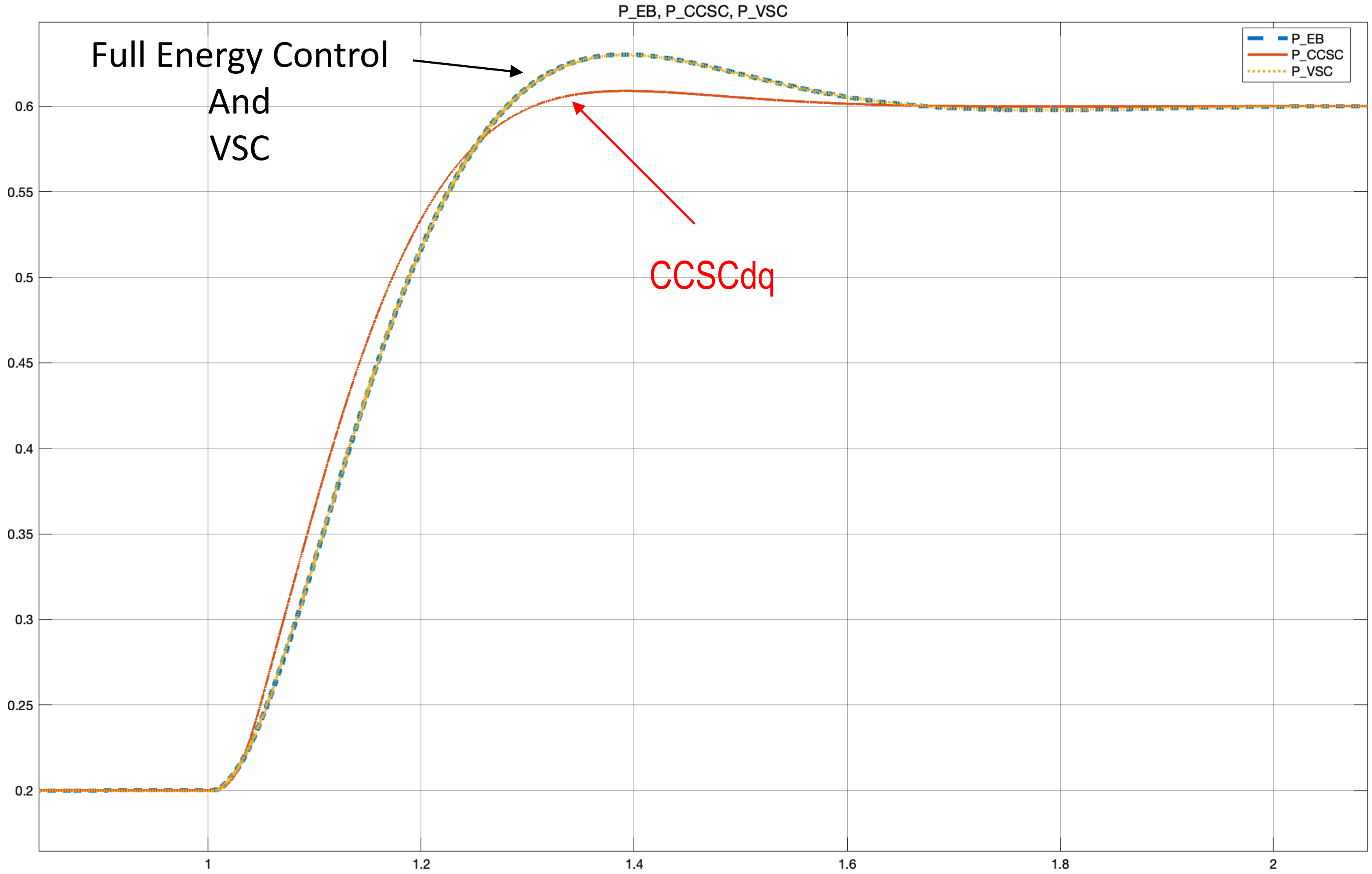
2 solutions for the energy control

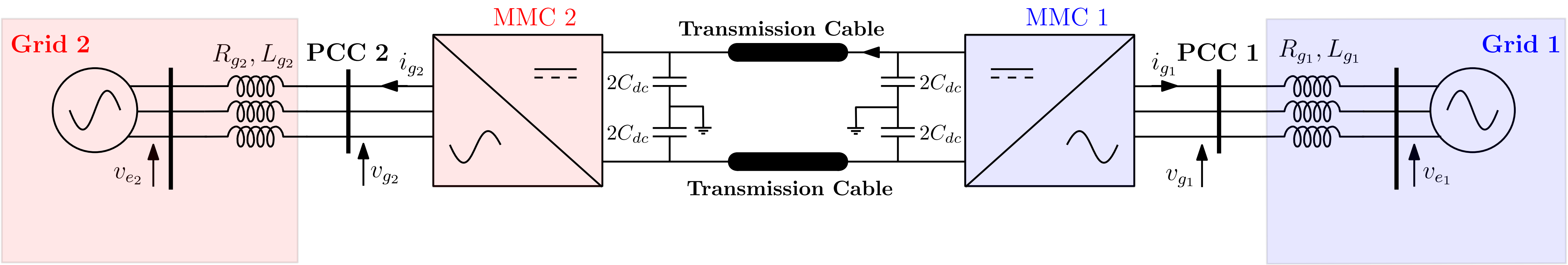
Energy loop : Full energy control

CCSCdq : No loops – the energy stabilize by it self at the good level

Step on the active power

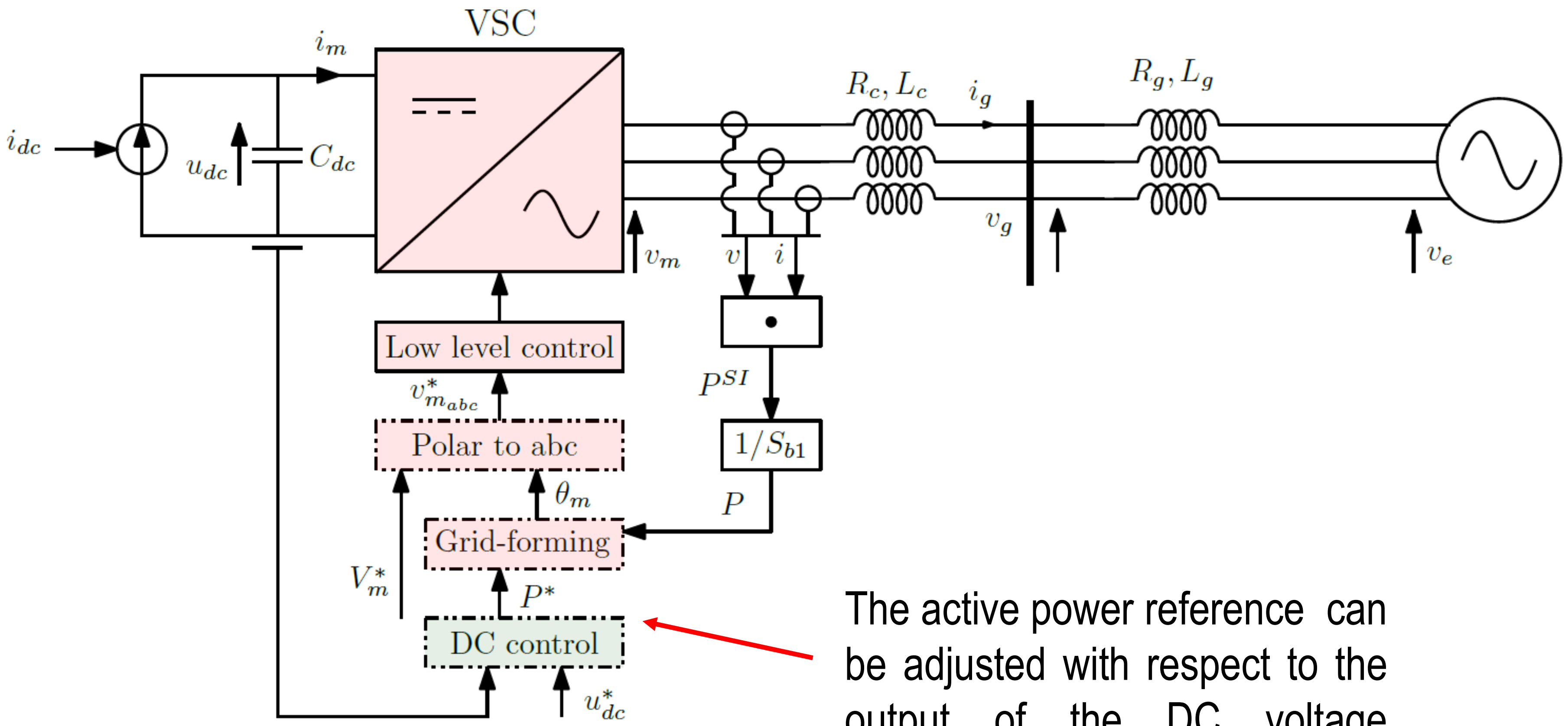
With a full Energy Control the dynamics of the active power loop is the same as for an ideal VSC





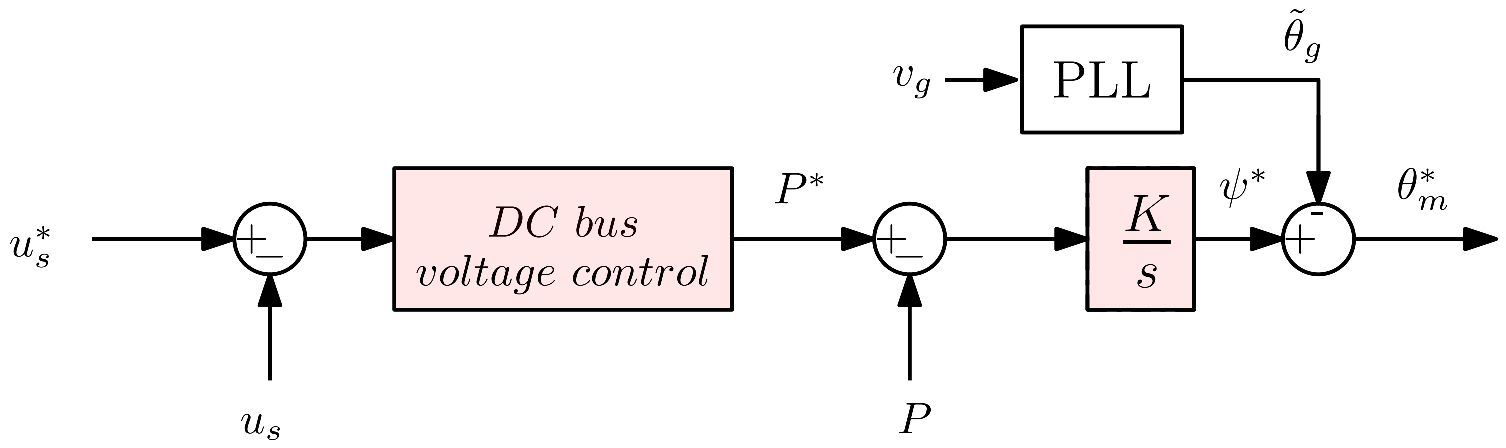
In an HVDC link, one converter is controlling the DC bus voltage, the other is controlling the power flow

Is the DC bus control compatible with the grid forming control ?

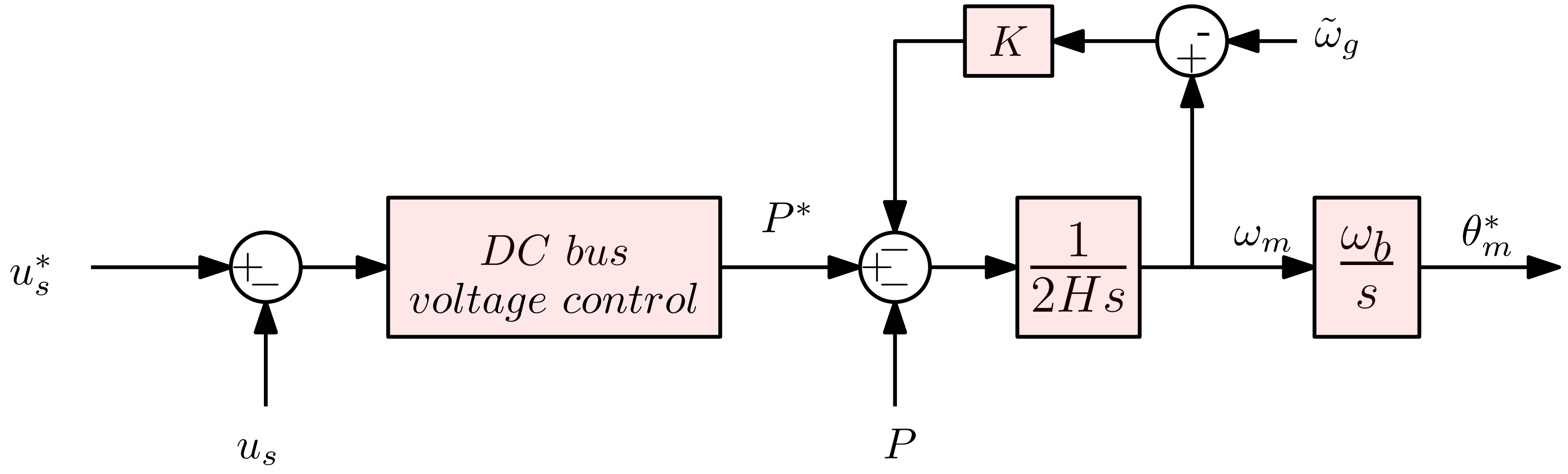


The active power reference can be adjusted with respect to the output of the DC voltage controller

With the **first type** of grid forming control, the converter behaves as a power injector
Hence, it is possible to add an external DC bus voltage loop



With the **second type** of grid forming control, the actions may have contradictory effects

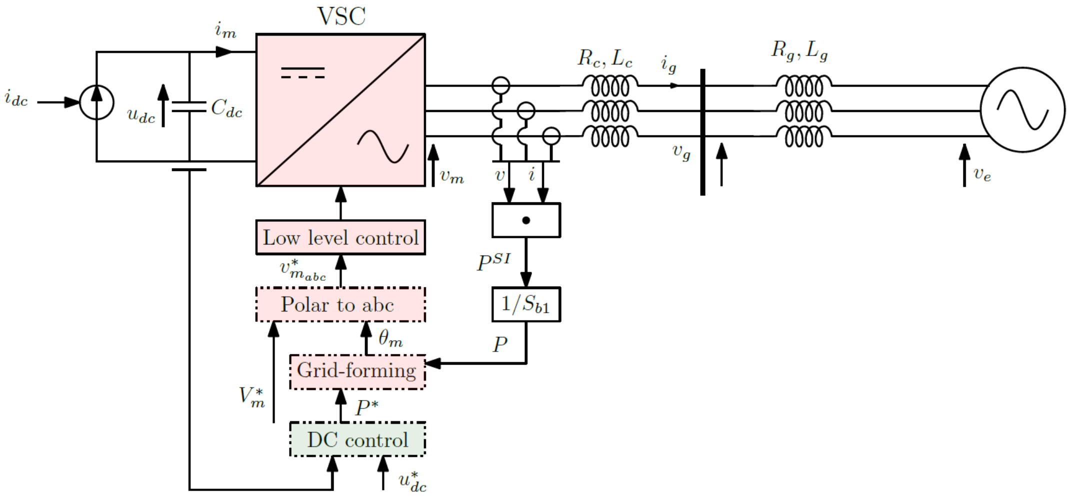


If the frequency decreases, P increases due to the inertial effect

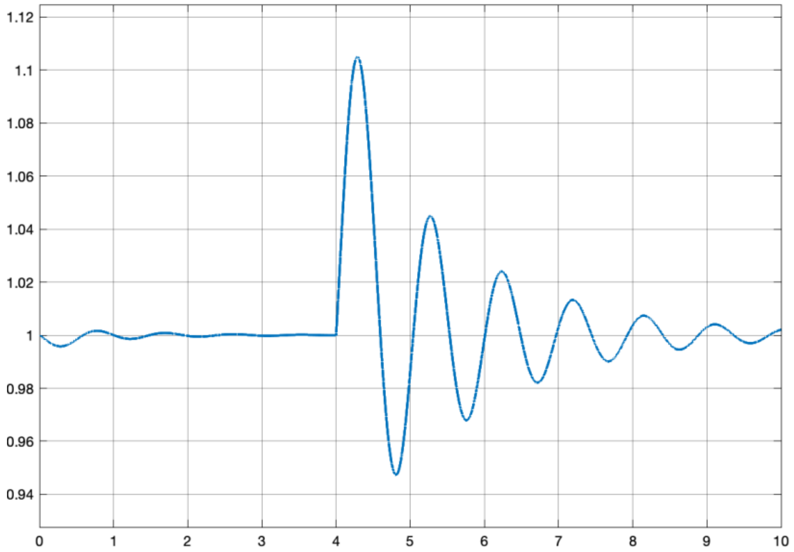
In the same time u_{dc} decreases so the output of the DC bus controller tends to decreases P^*

The DC bus control tends to counteract the inertial effect.

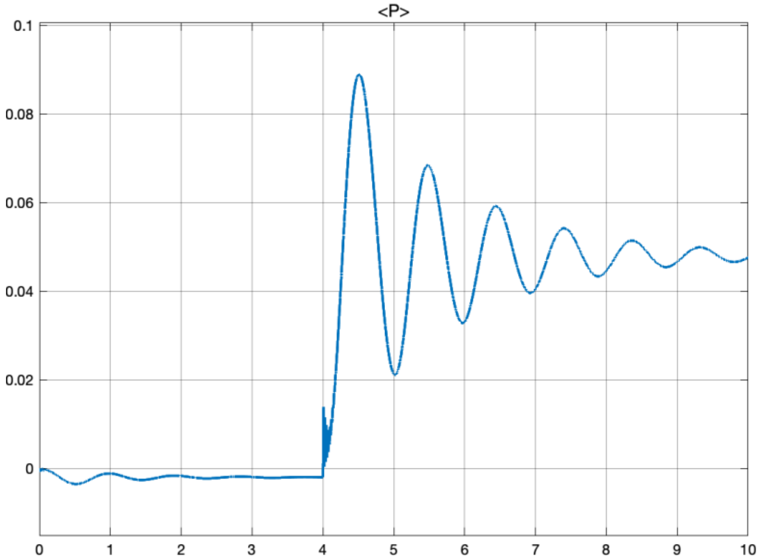
It may work if the inertial effect is not too high (1s for example) but in case of stronger inertial effect (5s for exampleà, this will lead to instable behaviour



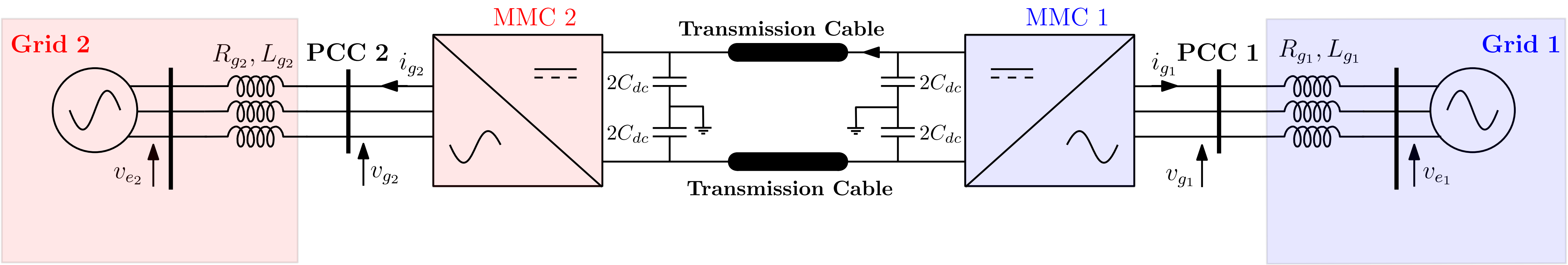
Udc



P



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

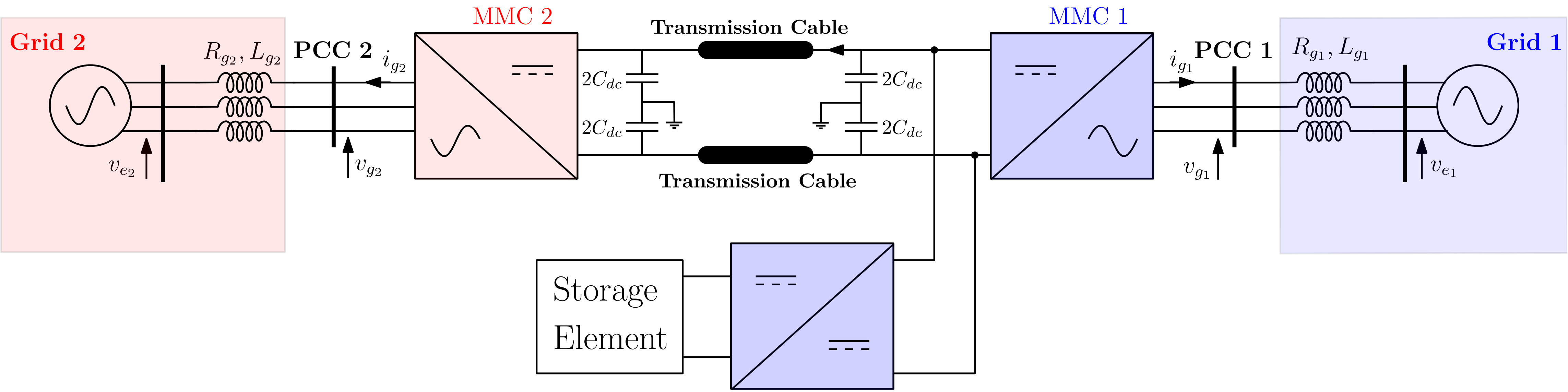


It is possible to have

A grid forming control (with or without inertial effect), on the station which controls the active power
A grid following converter on the station which controls the DC bus voltage

OR

A grid forming control (with or without inertial effect), on the station which controls the active power
A grid forming control with no or small inertial effect on the station which controls the DC bus voltage



If a strong inertial effect is required on both sides, a storage element is neeeded on the DC bus.

The storage element is controlling the DC bus voltage.
Importance of a good control of the level of energy in the storage.

Two mains types of grid forming control have been defined

1. One using a PLL
2. The other with no PLL

In the second case, two types of control

1. One with inertial effect
2. The other without inertial effect

The first control provides system strength but no inertial effect

The second control provides system strength and a possible inertial effect

Two mains types of grid forming control have been defined

1. One using a PLL
2. The other with no PLL

In the second case, two types of control

1. One with inertial effect
2. The other without inertial effect

For each control, there is a rigourous way to design the controller.

However in the second case, the response time depends on the grid impedance

In an extended version of the presentation, it is possible to show how to integrate a current loop in this kind of control

Even if the industrial controls are not implemented as explained in this presentation, this proposal could be help full to have a generic definition of the grid forming control. It is also very easy to characterize the overall behaviour of the grid forming converter.

The MCC behaves as an ideal VSC with grid forming control in case the energy is controlled inside the MMC

It is possible to have a grid forming control on each side of the HVDC link

But if a strong inertial effect is asked on each side, a storage is needed on the DC bus

Thanks for your attention